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Exploring Nonstandard Neutrino-Electron Interactions due to a New Light Spin-1 Boson

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Abstract

It is possible that nonstandard interactions of neutrinos arise from a new spin-1 particle with mass of tens of GeV or lower. Various existing data on neutrino-electron scattering and single-photon production in electron-positron collisions can impose considerable and complementary constraints on its couplings to the neutrinos and electron. If the new boson is sufficiently light, the constraints may significantly depend on its width as well as mass.

Various measurements have now established that neutrinos have mass and mix among themselves [1]. This constitutes evidence for physics beyond the minimal standard model (SM), as its neutrinos stay massless. Yet, in spite of the significant increase in knowledge about neutrinos, the origin of their mass remains an enigma [1]. It is widely expected, however, that the underlying new physics would also affect the electroweak neutral and charged currents, giving rise to so-called nonstandard interactions (NSI) in the neutrino sector [2, 3, 4]. In the literature they are usually taken to arise from the exchange of states above the electroweak scale, but it is also feasible that the exchanged particle is not heavy, with mass of order tens of GeV or lower. One of the simplest possibilities for such a particle is that it is a spin-1 boson.

Scenarios beyond the SM involving new light spin-1 bosons have been considered before in other contexts. Their existence in general is not only still compatible with present data, but also desirable, as they may offer explanations for some of the recent experimental anomalies and unexpected observations. These include the muon anomalous magnetic moment [5], the positron excess seen in cosmic rays [6], and the large like-sign dimuon charge asymmetry in semileptonic b-hadron decays measured at Fermilab [7].

Here we discuss the possibility recently explored in Ref. [8] that a nonstandard spin-1 boson under 100 GeV carrying no color or electric charge couples to both the neutrinos and electron. This allows us to concentrate on processes involving at least these leptons for which plenty of experimental data are available. Assuming that the new particle, hereafter denoted by X, is not necessarily a gauge boson, we keep its couplings to the leptons sufficiently general for a model-independent approach. This study complements those on neutrino NSI due to new physics above the electroweak scale (*e.g.*, [2, 4]).

We write the Lagrangian for the effective interactions of X with the neutrinos, ν_i, and electron, e, as

$$\mathcal{L}_X = -g_{\nu_i\nu_j}\bar{\nu}_i\gamma^\beta P_L\nu_j X_\beta - \bar{e}\gamma^\beta\big(g_{Le}P_L + g_{Re}P_R\big)e X_\beta\,, \tag{1}$$

where summation over $i, j = e, \mu, \tau$ is implicit, we have allowed for the possibility of X-induced neutrino flavor-change, and $P_{L,R} = \frac{1}{2}(1 \mp \gamma_5)$. Since compelling evidence for the existence of predominantly right-handed neutrinos is still absent [1], we have neglected their potential couplings to X. The Hermiticity of $\mathcal{L}_X$ implies that $g_{\nu_i\nu_j} = g^*_{\nu_j\nu_i}$ and that $g_{Le,Re}$ are real. In our model-independent framework, these parameters are free and can be family nonuniversal. For simplicity, we assume that X does not mix with the SM gauge bosons. We further assume that additional couplings which X may have

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with other fermions already satisfy the experimental restrictions to which the couplings are subject, but which we do not address in what follows.

In the SM, neutrino-electron interactions arise from diagrams with the W and Z bosons exchanged between the fermions. The relevant Lagrangian is

$$\begin{aligned}\mathcal{L}_{\rm SM} &= \frac{-g}{\sqrt{2}}\Big(\bar\nu_e\gamma^\beta P_L e\, W_\beta^+ + {\rm H.c.}\Big) \\ &\quad - \frac{g}{2c_{\rm w}}\,\bar\nu_i\gamma^\beta P_L\nu_i Z_\beta \\ &\quad - \frac{g}{c_{\rm w}}\,\bar e\gamma^\beta\Big(\bar g_L P_L + \bar g_R P_R\Big)e\, Z_\beta\,, \end{aligned} \tag{2}$$

$$\begin{aligned}\bar g_L &= s_{\rm w}^2 - \tfrac{1}{2}\,, \\ \bar g_R = s_{\rm w}^2 &= \sin^2\theta_{\rm W} = \sqrt{1-c_{\rm w}^2}\,, \end{aligned} \tag{3}$$

where g is the usual weak coupling constant and $\theta_{\rm W}$ the Weinberg angle.

One can extract bounds on the products $g_{\nu_i\nu_j}\, g_{Le,Re}$ of X couplings to the neutrino and electron in (1) from $\nu e \to \nu e$ and $\bar\nu e \to \bar\nu e$ collisions which have been observed in a number of low-energy experiments [9, 10, 11, 12, 13, 14, 15, 16, 17]. The data are generally consistent with SM expectations, but there is some room left for possible new physics.

In the SM, the amplitude for $\nu_e e^- \to \nu_e e^-$ at tree level comes from u-channel W-mediated and t-channel Z-mediated diagrams, while for $\nu_\mu e^- \to \nu_\mu e^-$ the W contribution is absent [18]. For these processes, the X interactions in (1) can induce t-channel diagrams. The latter type of X-mediated diagram is the only contribution at leading order to $\nu_i e^- \to \nu_j e^-$ for $j \neq i$ in the absence of other nonstandard mechanisms. Since the final neutrino in the νe scattering experiments is not detected, any one of the three light-neutrino flavors can occur in the final state. Hence for $\nu_i e^- \to \nu e^-$ and $i = e$ or μ we have the differential cross-section

$$\frac{d\sigma_{\nu_i e}}{dT} = \frac{1}{32\pi E_\nu^2 m_e} \sum_{j=e,\mu,\tau} \overline{\left|\mathcal{M}_{\nu_i e\to\nu_j e}\right|^2}\,, \tag{4}$$

where E_ν and T are, respectively, the energy of the incident neutrino and the kinetic energy of the recoiling electron both in the laboratory frame, m_e is the electron mass, and the general expressions for the squared amplitudes can be found in Ref. [8].

If m_X is not large compared to the momentum transfer in the collision, one needs to employ these general formulas to calculate the cross sections $\sigma_{\nu_i e}$. Moreover, for $\nu_e e$ scattering with incident neutrinos having been produced in μ^+ decays at rest and therefore not being monoenergetic, one has to integrate $\sigma_{\nu_e e}$ over the appropriate ν_e spectrum [19]. This leads to the flux-averaged cross-section [9]

$$\bar\sigma_{\nu_e e} = \int_0^{E_\nu^{\max}} dE_\nu\, \phi_{\nu_e}(E_\nu)\, \sigma_{\nu_e e}\,, \tag{5}$$

where the limits span the ν_e energy range in μ^+ decay, $E_\nu^{\max} = \big(m_\mu^2 - m_e^2\big)/(2m_\mu) \simeq 52.8\,{\rm MeV}$, and the spectrum function [19] $\phi_{\nu_e}(E_\nu) = 12\big(E_\nu^{\max} - E_\nu\big)E_\nu^2/(E_\nu^{\max})^4$ is normalized to unity.

In the $\bar\nu_e e^- \to \bar\nu e^-$ processes of interest, the incident antineutrinos originate from a nuclear reactor and hence do not share the same energy. Accordingly, the cross section again must be integrated over the reactor antineutrino spectrum [4, 19],

$$\bar\sigma_{\bar\nu_e e} = \int_{T_{\min}}^{T_{\max}} dT \int_{E_{\bar\nu}^{\min}}^{E_{\bar\nu}^{\max}} dE_{\bar\nu}\, \phi_{\bar\nu_e}(E_{\bar\nu})\, \frac{d\sigma_{\bar\nu_e e}}{dT}\,, \tag{6}$$

where $T_{\rm min,max}$ denote the experimental cuts on the kinetic energy T of the recoiling electron in the lab frame, $E_{\bar\nu}^{\min} = \frac{1}{2}T + \frac{1}{2}\big(2m_e T + T^2\big)^{1/2}$, and the spectrum, which extends to $E_{\bar\nu}^{\max} \sim 10\,{\rm MeV}$, is given by [3, 4]

$$\phi_{\bar\nu_e}(E_{\bar\nu}) = \sum_k a_k\, S_k(E_{\bar\nu})\,, \tag{7}$$

the sum of the spectra $S_k(E_{\bar\nu})$ from isotopes k with fractional contributions a_k.

Extra bounds on the products of X couplings to the leptons are available from $e^+e^- \to \nu\bar\nu\gamma$ scattering, which has been observed at LEP [20]. The SM amplitude at tree level is generated by five diagrams, three of which are mediated by the W and two by the Z. The X contributions are similar in form to the Z diagrams. Our computations including the X contributions agree with the literature [21]. The cross section can be written as

$$\begin{aligned}\sigma_{e\bar e\to\nu\bar\nu\gamma} &= \frac{1}{2(4\pi)^4\,(p_{e^+} + p_{e^-})^2} \\ &\quad \times \int dE_\gamma E_\gamma\, d\big(\cos\theta_\gamma\big)\, d\bar\Omega_\nu \\ &\quad \times \sum_{i,j=e,\mu,\tau} \overline{\left|\mathcal{M}_{e\bar e\to\nu_i\bar\nu_j\gamma}\right|^2}\,, \end{aligned} \tag{8}$$

where E_γ and θ_γ are the photon energy and angle with respect to the e^+ or e^- beam direction in the e^+e^- center-of-mass frame, $\bar\Omega_\nu$ denotes the solid angle of either ν or $\bar\nu$ in the $\nu\bar\nu$ center-of-mass frame, and the formulas for the squared amplitudes are given in Ref. [8]. We can now discuss our numerical results.

For $\nu_e e^- \to \nu e^-$, we employ the data on the flux-averaged cross-sections from the E225 experiment at