X(16.7) as the solution of the NuTeV anomaly [*]

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Abstract: A recent experimental study of excited ^{8}Be decay to its ground state revealed an anomaly in the angular distribution of the final states. This exceptional result is attributed to a new vector gauge boson X(16.7). We study the significance of this new boson, especially its effect in anomalies observed in long-lasting experimental measurements. By comparing the discrepancies between the Standard Model predictions and the experimental results, we find the values and regions of the couplings of X(16.7) to the muon and muon neutrino. In this work, we find that the newly observed boson X(16.7) may be the solution of both the NuTeV anomaly and the $(g-2)_\mu$ puzzle.

Keywords: NuTeV anomaly, new gauge boson, $(g-2)_\mu$ anomaly, neutrino trident production.

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1 Introduction

As a theory describing electroweak and strong interactions, the Standard Model (SM) has achieved great success, and has been tested at high precision. However, some experimental studies have pointed to the possibility of new physics beyond the SM. Examples include the non-zero masses of neutrinos, the existence of dark matter, and the muon anomalous magnetic moment. More fundamental challenges such as the hierarchy problem also pose severe challenges for the Standard Model in describing nature. Searching for new physics beyond the Standard Model (BSM) has become one of the major activities in physics. Numerous new physics models have been proposed. One of the simplest possibilities is $SU(3) \times SU(2)_L \times U(1)$ extended by a new gauge group $U(1)$.

A result in the ^{8}Be nuclear transition has brought a new challenge to our understanding of the electroweak interaction. In this reaction, ^{8}Be decays from an excited state to its ground state ^{8}Be$^* \to\ ^8$Be X, followed by a saturating decay $X \to e^+e^-$. A 6.8σ anomaly to the internal pair production was observed at a angle of $140°$ [1]. Although this extraordinary experimental phenomenon may be due to unidentified nuclear reactions or experi-

mental errors, it can also be attributed to a new vector boson X with a mass of 16.7 MeV, which mediates a weak BSM fifth force. In other words, the SM gauge group is extended by a new Abelian gauge group $U(1)_X$, which is one of the most natural extensions of the SM [2]. Based on this hypothesis, the values and regions of the first-generation charges of this protophobic gauge boson have been investigated. A new renormalizable model for this vector boson has been proposed [3]. The possibility of revealing this yet-to-be-verified gauge boson at other electron-positron colliders, such as at BESIII and BaBar has been evaluated [4].

Other than this phenomenal experimental discovery, discrepancies between experimental data and SM predictions have been exposed by several relatively old experimental studies, such as the anomalous magnetic moment of the muon $g-2$, and the NuTeV anomaly [5]. The NuTeV experiment found a 3σ deviation above the SM prediction for $\sin^2\theta_W$, and a large discrepancy between theoretical calculation and experimental measurements were also found earlier in an experiment measuring the $\bar\nu_e e$ elastic scattering cross-section [6]. Other experiments seem to point in the same direction, that there is a contribution from new physics in electroweak interactions [7–10]. The existence of a new light gauge boson

seems to be one of the most natural explanations [11], and in particular the muon g–2 anomaly can be related to a light vector boson Z_μ [12]. It is tempting to see whether the gauge boson X is responsible for these experimental anomalies. In this work, we study the BSM effect introduced by the Abelian gauge boson X to several well known experimental results, and investigate the values and regions of the coupling constant of this protophobic fifth force mediator to the muon and muon neutrino especially.

2   NuTeV anomaly

The discrepancy found by the NuTeV experiment is a well known result and has been discussed in many articles. Explanations of why the result for the value of $\sin^2\theta_W$ is three standard deviations above the SM prediction have been proposed in terms of both SM and BSM physics [13–16]. However, no definite conclusion can be made due to the large uncertainties. In this work, we show that the NuTeV anomaly can be fully attributed to the contribution of the X boson. The corresponding couplings of this new gauge boson can be chosen without contradicting the constraints given in Ref. [2].

We use the same Lagrangian proposed in Ref. [2]. The 16.7 MeV Abelian gauge boson X with field strength tensor $X_{\mu\nu}$ couples non-chirally to the SM fermions through the vector current $L = -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{1}{2}m_X^2 X_\mu X^\mu - JX^\mu$. The corresponding charge is noted as ε_f in units of e. The current $J_\mu = \sum_f e\varepsilon_f \bar{f}\gamma_\mu f$, however, can still be split into left-handed and right-handed pieces $J_\mu = \sum_f e\varepsilon_f \bar{f}_L\gamma_\mu f_L + \sum_f e\varepsilon_f \bar{f}_R\gamma_\mu f_R$. According to this model, the left-handed and right-handed fermions have identical charge. The mass of the X boson is far smaller than the center-of-mass energy of major electron-positron colliders. We adopt the conclusion given in [2], that the charges for up and down quarks satisfy the relation $\varepsilon_d = -2\varepsilon_u$. On the other hand, as illustrated in Ref. [17], if isospin is conserved for the decay studied in the Atomki experiment [1], the summation of ε_u and ε_d is constrained by

$$|\varepsilon_u + \varepsilon_d| \approx \frac{3.3 \times 10^{-3}}{\sqrt{\mathrm{Br}\left(\chi \to \mathrm{e}^+\mathrm{e}^-\right)}} \quad (1)$$

In this charge assignment, quark universality has been relaxed. The upper bound on $|\varepsilon_e|$ is provided by the measurement of electron magnetic moment $(g-2)_e$ [18]. The lower bound on $|\varepsilon_e|$ is given by the SLAC experiment E141 [19, 20]. The most strict upper bound on the coupling between electron and electron neutrino comes from the TEX-ONO experiment in Taiwan [21]. These

constraints can be summarized as follows

$$2 \times 10^{-4} \leqslant |\varepsilon_e| \leqslant 1.4 \times 10^{-3},$$
$$|\varepsilon_{\nu_e}\varepsilon_e|^{1/2} \leqslant 7 \times 10^{-5}. \quad (2)$$

The $(g-2)_\mu$ puzzle can be solved with ε_μ falling in the same range as ε_e. We will find out the constraint on ε_μ from the results of NuTeV, and the effect introduced by particle X on the number of neutrino flavors.

First of all, let us look at the effective four-fermion Lagrangian generated by X exchange given in [2]

$$L_X = -\frac{e^2}{2\left(m_X^2 - t\right)}\Big[\varepsilon_u \bar{u}_L\gamma_\mu u_L + \varepsilon_d \bar{d}_L\gamma_\mu d_L + \varepsilon_u \bar{u}_R^c\gamma_\mu u_R^c$$
$$+ \varepsilon_d \bar{d}_R^c\gamma_\mu d_R^c + \varepsilon_{\nu_\mu}\bar{\nu}_\mu\gamma_\mu\nu_\mu + \dots\Big]^2 \quad (3)$$

In the NuTeV experiment, nucleons are scattered by ν_μ, and the corresponding effective Lagrangian in SM at tree level can be expressed as

$$L_{\mathrm{eff}} = -2\sqrt{2}G_F \left([\bar{\nu}_\mu\gamma_\alpha\mu_L][\bar{d}_L\gamma^\alpha u_L] + \mathrm{h.c.}\right)$$
$$-2\sqrt{2}G_F \sum_{A,q} g_{Aq}[\bar{\nu}_\mu\gamma_\alpha\nu_\mu][\bar{q}_A\gamma^\alpha q_A], \quad (4)$$

where $A = \{L,R\}$, $q = \{u,d,s,\dots\}$ and the couplings g_{Aq} are in terms of the weak mixing angle $s_W \equiv \sin\theta_W$. The transfer momentum squared adopted by NuTeV is $t = -Q^2 = -20~\mathrm{GeV}^2$. What NuTeV measured is the ratio of neutral-current to charged-current deep-ineleastic neutrino-nucleon scattering total cross-sections. In the SM this ratio is given by

$$R = \frac{\mathrm{neutral\,currents}}{\mathrm{charged\,currents}} = \frac{\sigma_{\left(\nu_\mu N \to \nu_\mu X\right)} - \sigma_{\left(\bar{\nu}_\mu N \to \bar{\nu}_\mu X\right)}}{\sigma_{\left(\nu_\mu N \to \mu X\right)} - \sigma_{\left(\bar{\nu}_\mu N \to \mu^+ X\right)}}$$
$$= (g_l^2 - g_r^2) = \frac{1}{2} - \sin^2\theta_W \quad (5)$$

where $g_l^2 \equiv g_{Lu}^2 + g_{Ld}^2 = \frac{1}{2} - \sin^2\theta_W + \frac{5}{9}\sin^4\theta_W$, and $g_R^2 \equiv \frac{5}{9}\sin^4\theta_W$. The SM prediction with parameters determined by a fit to electroweak measurements is $\sin^2\theta_W = 0.2227 \pm 0.0004$ [22], while the NuTeV result is 3σ higher, $\sin^2\theta_W^{(\mathrm{on-shell})} = 0.2277 \pm 0.0013$. We next find out how the value of $\sin^2\theta_W$ is altered by the new gauge boson X, by calculating the effects of the X boson on the coupling constants g_L and g_R. Comparing (3) and (4), we obtain the contributions of the X mediated tree

level process to the coupling constants

$$\delta g_{Lu} = \frac{\varepsilon_u \varepsilon_{\nu_\mu} e^2}{2\sqrt{2} G_F (m_X^2 + Q^2)}$$

$$\delta g_{Ld} = \frac{-2\varepsilon_u \varepsilon_{\nu_\mu} e^2}{2\sqrt{2} G_F (m_X^2 + Q^2)}$$

$$\delta g_{Ru} = \frac{\varepsilon_u \varepsilon_{\nu_\mu} e^2}{2\sqrt{2} G_F (m_X^2 + Q^2)}$$

$$\delta g_{Rd} = \frac{-2\varepsilon_u \varepsilon_{\nu_\mu} e^2}{2\sqrt{2} G_F (m_X^2 + Q^2)} \tag{6}$$

Accordingly, the modification of $\sin^2 \theta_W$ is $\delta \sin^2 \theta_W = -\delta(g_L^2 - g_R^2) = \dfrac{6\pi\alpha\varepsilon_u \varepsilon_{\nu_\mu}}{\sqrt{2} G_F (m_X^2 + Q^2)} \approx 5 \times 10^{-3}$. Assuming $\varepsilon_{\nu_\tau} \sim \varepsilon_{\nu_\mu}$, we obtain the charges

$$\varepsilon_{\nu_\mu} \simeq \pm 2.0 \times 10^{-3} \tag{7}$$

$$\varepsilon_u \simeq \pm 5.7 \times 10^{-3} \tag{8}$$

by combining this formula with (1) and taking the upper limit of $\varepsilon_e \sim 1.4 \times 10^{-3}$. The difference between the experimental value and SM expectation of the Weinberg angle is resolved. If the NuTeV anomaly is entirely due to the new U(1) particle X , the absolute value of its coupling to ν_μ has to be much larger than the absolute value of its coupling to ν_e. The above result can also be viewed as an upper bound for ε_{ν_μ}.

To test the above calculation, let us check how the ratio R is modified by the gauge boson X. After introducing X, the ratio is proportional to

$$R \propto \left[\sum_{u,d} G_F c_v^q c_a^q\right]_{\text{eff}} = \sum_{u,d}\left[G_F c_v^q c_a^q + \frac{e^2}{\sqrt{2}}\left(\frac{\varepsilon_l^\nu c_a^q \varepsilon_l^q}{Q^2}\right)\right], \tag{9}$$

where $c_v^f = I_3^f - 2Q^f \sin^2 \theta_W$, and $c_a^f = I_3^f$ are the quantum numbers in GWS theory. The measured value of $\left[\sum_{u,d} G_F c_v^q c_a^q\right]_{\text{eff}}$ is $(3.1507 \pm 0.0288) \times 10^{-6}$, while the SM expectation is 3.2072×10^{-6} [23]. The discrepancy can be explained by the second term in the brackets of (9) introduced by gauge boson X. Substituting our result for ε_{ν_μ}, and (1) into this term, we find the discrepancy is indeed redeemed. Comparing the value of $|\varepsilon_{\nu_\mu}|$ to the constraints in (2), we notice that if the NuTeV anomaly is mainly due to the contribution from the new vector boson X, then like quark universality, neutrino universality has to be broken as well.

3 Number of neutrino flavors

In order to check the plausibility of this $SU(3) \times SU(2)_L \times U(1) \times U(1)_X$ model, we would like to test it against the well known number of neutrino flavors N_ν. This number is most precisely measured through the Z production process in e^+e^- collisions. The SM value for the ratio of the neutrino to charged leptonic partial width is used in order to reduce the model dependence

$$N_\nu = \frac{\Gamma_{\text{inv}}}{\Gamma_l}\left(\frac{\Gamma_l}{\Gamma_\nu}\right)_{SM} \tag{10}$$

where Γ_{inv} is the invisible decay width of the Z boson obtained experimentally, and Γ_ν is the tree level SM expectation of the width of Z boson decays into certain flavors of neutrino pairs. Γ_ν represents the invisible partial width, which is determined by subtracting the visible partial widths from the total Z width. It is assumed that each light neutrino flavor makes an identical contribution Γ_ν to the neutrino partial width due to lepton universality. The visible width corresponds to Z decays into quarks and charged leptons. A combination of several experimental measurements gives the result $N_\nu = 2.984 \pm 0.008$ [24]. To find out if the propagator of the X boson will alter N_ν significantly, we calculate the distribution of the cross-section for the process $e^+e^- \to \nu\bar{\nu}$ shown in Fig. 1. Since lepton universality is broken in the extended model, the contribution of the decay to each neutrino flavor is calculated separately. In our computation, we take the upper bounds of the coupling constants, and assume the X boson couples equally to muon neutrino and tau neutrino.
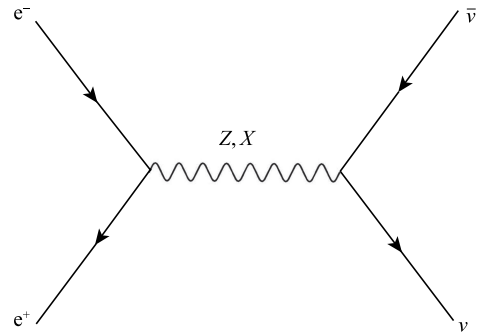

Fig. 1.   The leading diagram that contributes to X-boson production in electron-positron collisions.

The result is displayed in Fig. 2, where even the upper bounds of the coupling constants is too small to have any noticeable effect on the decay width of the Z boson. Our result for the coupling constant ε_{ν_μ} is safe from contradicting the well tested conclusion of the number of neutrino flavors.
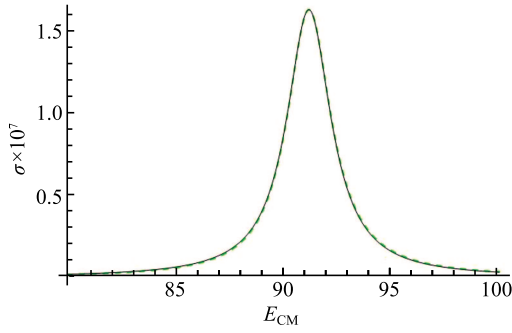
Fig. 2.   (color online) Taking the upper bounds of ε_e, and $|\varepsilon_{\nu_\mu}| = 6 \times 10^{-3}$ from the previous subsection, we calculate the distribution of the cross-section for the process $e^+e^- \to \nu\bar{\nu}$. The solid line is the SM prediction, and the green dashed line is the distribution.

4   Neutrino trident production

Models based on gauged muon number L_μ are strictly constrained by the SM trident production of neutrinos, where a pair of muon and anti-muon is produced in the scattering of muon neutrinos in the Coulomb field of a target nucleus. A new force mediated by a heavy vector boson is excluded as a solution of the $(g-2)_\mu$ anomaly [25]. The existence of a vector gauge boson with a mass of 16.7 MeV would also be excluded in the $L_\mu - L_\tau$ model [11] by combining the measurements of neutrino trident production with our result for ε_{ν_μ}. We will show here that there is room for the X boson, if the simple $SU(3) \times SU(2)_L \times U(1) \times U(1)_X$ model is adopted.

The contribution of X to the trident production of neutrinos at tree level is shown in Fig. 3. In the SM, the propagator of X is replaced with the W and Z boson propagators. Unlike in the $L_\mu - L_\tau$ model, the X couplings to muons and muon-neutrinos may have the same or opposite sign. Therefore, the trident production may be reduced or enhanced by the interference between the X-boson and W-boson (Z-boson). We adopt a calculation procedure using the equivalent photon approximation (EPA) [11, 26, 27]. The full cross-section of a neutrino scattering with a nucleus N can be written as a convolution of two separate parts

$$\sigma\left(\nu_\mu N \to \nu_\mu N \mu^+ \mu^-\right) = \int \sigma\left(\nu_\mu \gamma \to \nu_\mu \mu^+ \mu^-\right) P\left(s, q^2\right), \quad (11)$$

where the first part of the integrand $\sigma\left(\nu_\mu \gamma \to \nu_\mu \mu^+ \mu^-\right)$ is the cross-section for a neutrino scattered off a real photon; the second part $P\left(s, q^2\right) = \dfrac{Z^2 e^2}{4\pi^2} \dfrac{\mathrm{d}s}{s} \dfrac{\mathrm{d}q^2}{q^2} F^2\left(q^2\right)$, is the probability of creating a virtual photon with virtuality q^2 and energy $\sqrt{s}$ in the center-of-mass frame of

the neutrino and a real photon. The virtual photon is created in the electromagnetic field of the nucleus N with charge Ze and a electromagnetic form-factor (FF) $F\left(q^2\right)$. Generally, the real photon cross-section can be written as

$$\sigma^{(\mathrm{SM+X})} = \sigma^{(\mathrm{SM})} + \sigma^{(\mathrm{inter})} + \sigma^{(\mathrm{X})}, \quad (12)$$

where the second term comes from the interference between the SM and the X contributions. The differential cross-sections for each of them have a general symbolical form

$$\mathrm{d}\sigma = \frac{1}{2s} \mathrm{dPS}_3 \left(\frac{1}{2} M^2\right) \frac{G_F^2 e^2}{2}. \quad (13)$$

Here, $G_F = \sqrt{2}g^2/(8M_W^2)$ is the Fermi constant, and dPS_3 is the 3-body phase-space. In our calculation, the squared amplitudes M^2 are generated by FeynCalc [28]. By replacing the propagator with the inverse of the mass of the mediator boson squared, and omitting terms proportional to the muon mass in the numerator, we recover the SM expression given in Refs. [11, 29]. The phase-space integration is numerically calculated with Vegas [30]. Our calculation verify the analytic expression of the leading log approximation for real photon cross-section in the SM [11].

By numerically integrating the real-photon cross-section with the probability distribution function $P\left(s, q^2\right)$ in the range of $4m_\mu^2 < s < 2E_{\nu_\mu} q$ and $2m_\mu^2/E_{\nu_\mu} < q < \infty$, we obtain the total cross-section for $\nu_\mu N \to \nu_\mu N \mu^+ \mu^-$. We use a simple exponential function to mimic the nucleus form factor [31]. To test our calculation, we reproduced the prediction of the SM and V-A theory [31, 32].

Neutrino trident production has been studied by several experiments [33–35], among which the measurement from the CCFR collaboration provides the strongest constraints on the parameter space, and is used in our study. The CCFR collaboration detected trident events by scattering a neutrino beam with a mean energy of $E = 160$ GeV with an iron target. The ratio of the cross-section they obtained to the SM prediction is $\sigma_{CCFR}/\sigma_{SM} = 0.82 \pm 0.28$. At this energy level, it is safer not to make any approximations in the formulation of the amplitudes. In our calculation, we keep all the gauge boson propagators, and all the terms containing muon mass. By combining the CCFR measurement with our numerical result, we obtain the following range for the first-generation charge of the gauge boson X

$$-2.0 \times 10^{-5} < \varepsilon_{\nu_\mu} \varepsilon_\mu < 6 \times 10^{-7}. \quad (14)$$

We notice here that if ε_{ν_μ} and ε_μ have the same sign, and particle X is fully responsible for the NuTeV anomaly, the value of ε_μ is strictly restricted to be less than 3×10^{-4}, which excludes the possibility for the gauge

boson X to be the solution of the $(g-2)_\mu$ anomaly [36]. However, if ε_{ν_μ} and ε_μ have opposite signs, the constraint on ε_μ is greatly relaxed to $|\varepsilon_\mu| < 1 \times 10^{-2}$, making it a candidate for solving the $(g-2)_\mu$ puzzle. Future experiments such as LBNE may provide more data on neutrino trident production [11], which may lead to decisive analysis of the coupling of X(16.7) to neutrinos.
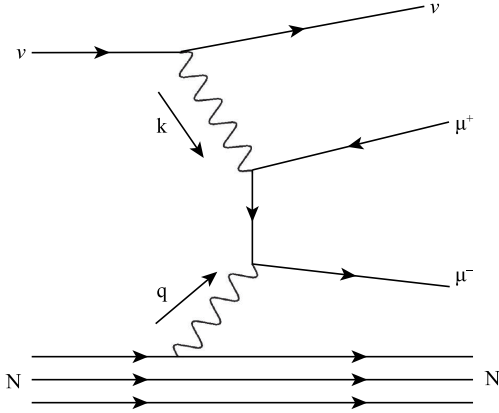

Fig. 3.   The trident process at tree level.

5   Conclusions

Unlike heavy Z′ boson that has been widely discussed in the literature [37–40], the newly found gauge boson X is very light. It is quite exciting to know that low energy experiments still have the possibility of finding such a light boson. A commonly asked question is what the constraints are for this new particle from preexisting experimental measurements. We have investigated some of the consequences of this unusual vector gauge boson X. The SM gauge group $SU(3) \times SU(2)_L \times U(1)$ extended by an Abelian gauge groups $U(1)_X$ was adopted in our calculation. Its implications for the NuTeV anomaly were studied. First of all, we found that the charge has to be $|\varepsilon_{\nu_\mu}| \simeq 2 \times 10^{-3}$, with the opposite sign to ε_u, in order to attribute the NuTeV anomaly entirely to the gauge boson X(16.7). We have proven that this value, although it is comparable to or even larger than the coupling constants for the other fermions, is still too small to allow any effect on the experimental measurement of the number of neutrino flavors to be noticed in previous experiments. Next, we studied the neutrino trident production. Comparing the numerical calculation of this process with measurements from CCFR results in a powerful constraint on the parameter space of the model: $-2.0 \times 10^{-5} < \varepsilon_{\nu_\mu} \varepsilon_\mu < 6 \times 10^{-7}$. When combined with the requirement of explaining the discrepancy in the muon $(g-2)$, unlike what would happen to a heavy vector boson [25], the light gauge boson X(16.7) survived. Particularly, if ε_{ν_μ} and ε_μ have the same sign, the vector gauge boson X cannot be responsible for both the NuTeV and the $(g-2)_\mu$ anomaly. However, if ε_{ν_μ} and ε_μ have opposite signs, X(16.7) can indeed be the solution to both of these puzzles. On the other hand, $|\varepsilon_{\nu_\mu}|$ would be smaller, if other effects such as the strange sea asymmetry or isospin violation take partial responsibility for the discrepancy between NuTeV and the SM prediction. In that case, a gauge boson X with $\varepsilon_{\nu_\mu} \varepsilon_\mu > 0$ can be the solution of the $(g-2)_\mu$ anomaly. Finally, although the coupling of the X boson to muon neutrinos deduced from the NuTeV anomaly is significantly larger than the coupling of X to electron neutrinos [2], it survives the constraint deduced from the CHARM II experiment [41], if the uncertainties of measurements are taken into account. This value of coupling may lead to a deformation of the invariant mass distribution of e^+e^- in the final state for the differential cross section proposed to search for the X boson [4].

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