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Realistic model for a fifth force explaining anomaly in ${}^{8}Be^{*} \to {}^{8}Be\, e^{+}e^{-}$ decay

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Abstract

We propose a theoretical model to explain a $6.8\,\sigma$ anomaly recently reported in the opening angle and invariant mass distributions of $e^{+}e^{-}$ pairs produced in excited ${}^{8}Be^{*}$ nuclear transition to its ground state ${}^{8}Be$. The anomaly is explained by a fifth force mediated by a 17 MeV X boson through the decay ${}^{8}Be^{*} \to {}^{8}Be\, X$ followed by $X \to e^{+}e^{-}$. The X boson comes from extension of the standard model with two additional U(1) gauge symmetries producing a protophobic pure vector current interaction with quarks. The model also contains axial-vector current interaction. Although the existent axial-vector current interactions are strongly constrained by the measurement of parity violation in e-quark scattering, their contributions cancel out in the iso-scalar interaction for ${}^{8}Be^{*} \to {}^{8}Be\, X$. It is remarkable that the model parameters need to explain the anomaly survive all known low energy experimental constraints. The model may also alleviate the long-standing $(g-2)_{\mu}$ anomaly problem and can be probed by the LHCb experiment.

1. Introduction

Recently, studies of decays of an excited iso-scalar state ${}^{8}B_{e}^{*}$ of ${}^{8}Be$ to its ground state have found a $6.8\,\sigma$ anomaly in the opening angle and invariant mass distribution of $e^{+}e^{-}$ pairs produced in these transitions [1]. The discrepancy from expectations may be explained by unknown

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nuclear reactions or unidentified experimental effects, the observed distribution fits well by postulating the existence of a fifth force mediated by a new boson X that is produced on-shell in ${}^8Be^* \to {}^8Be\ X$ and decays promptly via $X \to e^+e^-$. The authors of Ref. [1] have simulated this process, including the detector energy resolution, which broadens the m_{ee} peak significantly. They find that the X boson mass should be $m_X = 16.7 \pm 0.35(\text{stat}) \pm 0.5(\text{sys})$ MeV. An anomaly had previously been reported in an excited iso-vector state ${}^8B_e^{*'}$ decays to the ground state [2]. It is now excluded [3]. If the observed anomaly in ${}^8B_e^*$ decays originates from a new particle of mass 16.7 MeV, in principle it may also be seen in ${}^8B_e^{*'}$ decays. The absence of new particle creation in the ${}^8B_e^{*'}$ decay has been suggested to be due to kinematical suppression [4]. We will be, therefore, study the implications of the anomaly in ${}^8B_e^* \to {}^8B_e e^+e^-$ here.

The X boson is likely a vector boson which couples non-chirally to the SM fermions [4],

$$L = -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{1}{2}m_X^2 X_\mu X^\mu - X_\mu J_X^\mu$$
$$\text{with } J_\mu = \sum_{f=u,d,e,\nu_e,\ldots} e\varepsilon_f^v J_\mu^f = \sum_{f=u,d,e,\nu_e,\ldots} e\varepsilon_f^v \bar{f}\gamma_\mu f\,. \tag{1}$$

Here the superscript "v" on ε_f^v indicates the vector current coupling nature.

To explain the experimental data, the couplings ε_f^v are determined from the following considerations [4]. Assuming ${}^8Be^* \to {}^8B_e\ X$ followed by $X \to e^+e^-$ saturating X decay, one obtains

$$|\varepsilon_p^v + \varepsilon_n^v| \approx 1.0 \times 10^{-2}\,, \quad |\varepsilon_e^v| \gtrsim 1.3 \times 10^{-5}\,. \tag{2}$$

Here the fact that the interaction matrix element of X with ${}^8Be$ and ${}^8Be^*$ is iso-scalar interaction has been taken into account which implies that the interaction is proportional to $\varepsilon_p^v + \varepsilon_n^v$. Note that $\varepsilon_{p,n}^v$ to light quark coupling parameter ε_q^v are related by $\varepsilon_p^v = 2\varepsilon_u^v + \varepsilon_d^v$ and $\varepsilon_n^v = \varepsilon_u^v + 2\varepsilon_d^v$.

The vector parameters ε_i^v are also directly constrained from other experimental data. An important one comes from $\pi^0 \to X\gamma$ where the decay width is proportional to $N_\pi = (Q_u\varepsilon_u^v - Q_d\varepsilon_d^v)^2$ resulting from a calculation similar to anomaly induced $\pi^0 \to \gamma\gamma$. Saturating the experimental limit $N_\pi = (2\varepsilon_u^v + \varepsilon_d^v)/9 = \varepsilon_p^v/9 < \varepsilon_{max}^2/9$ with $\varepsilon_{max} = 8 \times 10^{-4}$ [5], one obtains the constraints for ε_p^v and the allowed range for ε_n^v [4],

$$|\varepsilon_p^v| < 1.2 \times 10^{-3}\,, \quad |\varepsilon_n^v| : (2 \sim 10) \times 10^{-3}\,. \tag{3}$$

Here the upper part of the ε_n^v range includes the coupling for the best fit branching ratio for $m_X = 16.7$ MeV, and the lower part presumably includes the best fit value for the larger m_X that simultaneously explain the ${}^8B_e^*$ signal and the ${}^8B_e^{*\prime}$ null results, as argued in Ref. [4].

Therefore the coupling ε_p^v is suppressed compared with ε_n^v. It has been suggested in Ref. [4] that the interaction might be protophobic with $\varepsilon_p^v = 0$. In this case, the ranges allowed for $\varepsilon_{u,d}^v$ are

$$\varepsilon_u^v : \pm(0.7 \sim 3.3) \times 10^{-3}\,, \quad \varepsilon_d^v : \mp(1.4 \sim 6.6) \times 10^{-3}\,. \tag{4}$$

Requiring ε_e^v to satisfy the lower bound from SLAC E141 experiment [6], the stringent constraint from electron anomalous magnetic dipole moment $(g-2)_e$ [7], and also the precision studies of $\bar{\nu}_e - e$ scattering from TEXONO [8], one yields

$$2 \times 10^{-4} < |\varepsilon_e^v| < 1.4 \times 10^{-3}\,, \quad |\varepsilon_e^v\varepsilon_{\nu_e}^v|^{1/2} < 7 \times 10^{-5}\,. \tag{5}$$

In general the X boson may also have axial-vector current couplings to the SM fermions, i.e.

$$e\varepsilon_f^a \bar{f}\gamma_\mu\gamma_5 f\,. \tag{6}$$

However, the X boson is only allowed to give an extremely tiny contribution to the decay width of $\pi^0 \to e^+e^-$. This means that the X boson cannot have a sizable axial-vector current interaction with both the electron and the first-generation quarks. One has to check if the strong constraints from this and also possibly other processes can be satisfied.

The X boson interactions discussed above are based on an effective theory approach. No information about where the X boson come from, how the X boson interact with generations of fermions in the SM and associated experimental constraints. It would be desirable to have the X boson be part of a consistent theory respecting the standard model (SM) symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$ with interactions with other SM particles specified. This makes the task non-trivial because one has to take into account more theoretical and experimental constraints.

In this work we propose a theoretical model to first successfully realize this goal. Specifically we consider new gauge symmetries $U(1)_{Y'}$ and $U(1)_X$ in addition to the SM gauge group. Under the $U(1)_{Y'}$, three generations of the SM fermions carry different quantum numbers to produce the unique protophobic current interactions. The X boson mediating the fifth force is just the $U(1)_X$ gauge boson and couples to the SM fermions through the $U(1)_{Y'}$ and $U(1)_X$ kinetic mixing. The X boson has both vector and axial-vector current couplings. The vector current interactions are protophobic, while the axial-vector currents are not protophobic but have no contributions to the iso-scalar interaction for ${}^8Be^* \to {}^8Be\, X$. Within the allowed parameter space, this model can also alleviate the long-standing $(g-2)_\mu$ anomaly problem and can be tested by the LHCb experiment.

2. A realistic model

From theoretical side, the SM fermions appear in form of chiral fields, implying that introduction of new gauge boson interaction may generate gauge anomalies which is not allowed for a consistent theory. Without un-necessarily introducing too many new ingredients beyond the SM, we cancel the gauge anomaly by using the anomaly cancellation among different generations, similar to the gauge anomaly free model for $L_i - L_j$ in the literature [9]. The appearance of chiral fields in general makes the X boson interaction not purely vector current type which may lead to complications and need to be carefully treated. Also the X boson may interact with different generations in general, there are more constraints from data. It is remarkable that the model we propose can explain all of the data consistently with moderate extension beyond SM. We provide the details in the following.

The key to our construction is to have a protophobic vector current first and then accommodate the constraints from ${}^8Be^* \to {}^8BeX$ and $\pi^0 \to X\gamma$. To achieve this we introduce a $U(1)_{Y'}$ gauge symmetry whose vector current is protophobic. The assignment of quantum numbers for the three generations of fermions, under the $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{Y'}$, are as the following

$$\begin{aligned}
&Q_L^1 : (3,\ 2,\ 1/6)(-1)\,, && u_R^1 : (3,\ 1,\ 2/3)(5)\,, && d_R^1 : (3,\ 1,\ -1/3)(-7)\,,\\
&L_L^1 : (1,\ 2,\ -1/2)(\beta)\,, && e_R^1 : (1,\ 1,\ -1)(\beta)\,, && \\
&Q_L^2 : (3,\ 2,\ 1/6)(1)\,, && u_R^2 : (3,\ 1,\ 2/3)(-5)\,, && d_R^2 : (3,\ 1,\ -1/3)(7)\,,\\
&L_L^2 : (1,\ 2,\ -1/2)(-\beta)\,, && e_R^2 : (1,\ 1,\ -1)(-\beta)\,, &&
\end{aligned} \tag{7}$$

and the third generation does not have any $U(1)_{Y'}$ charges. One can easily check that the model is gauge anomaly free. Up to variations of exchange the quantum numbers between different generations, the above is unique in realizing protophobic vector current interaction.

Expanding the interactions between the $U(1)_{Y'}$ gauge boson Y' and the SM fermions, $Y'_\mu J^\mu_{Y'}$, we have the current coupling to the Y' field,

$$J^\mu_{Y'} = g_{Y'}\left[\bar{u}\gamma^\mu(4+6\gamma_5)u - \bar{d}\gamma^\mu(8+6\gamma_5)d + \beta\bar{e}\gamma^\mu e + \frac{\beta}{2}\bar{\nu}_e\gamma^\mu(1-\gamma_5)\nu_e\right],$$
$$- g_{Y'}\left[\bar{c}\gamma^\mu(4+6\gamma_5)c - \bar{s}\gamma^\mu(8+6\gamma_5)s + \beta\bar{\mu}\gamma^\mu \mu + \frac{\beta}{2}\bar{\nu}_\mu\gamma^\mu(1-\gamma_5)\nu_\mu\right], \tag{8}$$

with $g_{Y'}$ being the $U(1)_{Y'}$ gauge coupling.

We cannot identify the Y' boson as the desired X boson yet. The reason is that the Higgs scalars giving the SM fermion masses will have non-trivial quantum numbers for both the SM and $U(1)_{Y'}$ gauge groups and will contribute to the W, Z and Y' gauge boson masses. If Y' is X, it must have a small mass 17 MeV, and the vacuum expectation value (VEV) should be much smaller than electroweak scale for a $g_{Y'}$ explaining the anomalous ${}^8Be^* \to {}^8Be\, e^+e^-$. Another problem is that the couplings of neutrinos to Y' are too large to satisfy the constraints mentioned previously. These problems must be solved for a realistic model.

We find that light mass problem can be solved by introducing an additional gauge symmetry $U(1)_X$ to the model, under which the SM fermions are trivial. But through a kinetic mixing of $U(1)$ gauge fields [10], $-(\epsilon/2)Y'_{\mu\nu}X^{\mu\nu}$, the X boson does interact with the SM fermions. This term maintains the renormalizability of the theory. The parameter ϵ is a free parameter of the theory. By diagonalizing and normalizing the gauge fields Y' and X properly, up to the leading order in ϵ, we have the couplings of the X boson to the $J^\mu_{Y'}$ current as,

$$\epsilon X_\mu J^\mu_{Y'}\,. \tag{9}$$

Since the X boson does not carry the SM gauge group quantum numbers, one can generate a small mass $m_X^2 = (g_X x_\rho v_\rho)^2$ by introducing an SM-singlet scalar ρ with a $U(1)_X$ charge x_ρ and a VEV $v_\rho/\sqrt{2}$. Here g_X is the $U(1)_X$ gauge coupling. Clearly, this small mass m_X does not affect the usual electroweak scale. We will assume the X boson to have a mass of 17 MeV. At the same time, one can introduce another scalar singlet σ with a $U(1)_{Y'}$ charge y'_σ and a VEV $v_\sigma/\sqrt{2}$ to contribute to the Y' mass with $m^2_{Y'} = (g_{Y'}y'_\sigma v_\sigma)^2$, assuming $m_{Y'}$ of the order of TeV, the contributions from the Higgs scalars transforming as the SM iso-doublets can be neglected since their VEVs are at the electroweak scale. Note also that to order ϵ, the Z boson does not mix with the X boson in the model.

We now discuss how to suppress the couplings of the X boson to the electron neutrino ν_e. This is achieved by mixing ν_e with a new vector-like fermion $S = S_L + S_R$ which is a singlet under the SM and $U(1)_{Y'}$ gauge groups but carry a $U(1)_X$ charge x_S. One can also introduce three gauge-singlet fermions N_{Ri} $(i = 1, 2, 3)$ to facilitate a canonical seesaw mechanism for generating the small neutrino masses. Let us take the first generation into account for illustration. With three iso-doublet Higgs scalars $\phi_e(0,0)$, $\phi_{\nu_e}(\beta,0)$, and $\eta(\beta,-x_S)$, where the brackets following the fields describe the transformations under the $U(1)'_Y \times U(1)_X$ gauge groups, the terms responsible for the first-generation lepton masses are

$$L = -y_e\bar{L}^1_L\tilde{\phi}_e e_R - y_N\bar{L}^1_L\phi_{\nu_e}N_R - \frac{1}{2}M_N\bar{N}^c_R N_R - f_S\bar{L}^1_L\eta S_R - m_S\bar{S}_L S_R + \text{H.c.} \tag{10}$$

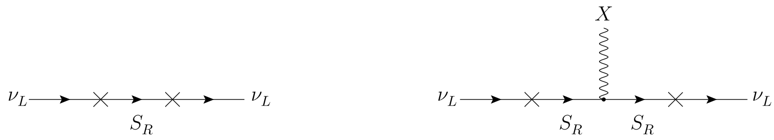

Fig. 1. The effects of the $\nu_L - S$ mixing, generation of the U_s matrix (left) and modification of the interaction of the X boson with the left-handed neutrinos (right).

After integrating out the heavy right-handed neutrinos N_R, the Majorana masses for light neutrinos ν_L will be generated through the seesaw mechanism. We also need to integrate out the heavy vector-like fermions $S_{L,R}$ as shown in the left diagram of Fig. 1. This will also generate a non-zero coupling for X with ν_L, see the right diagram of Fig. 1. We emphasize that the mixing between the vector-like fermion and the electron neutrino will not be stringently constrained by the neutrino masses, instead, it will affect the Dirac equations of the left-handed electron neutrino, i.e.

$$\mathcal{L} \supset i\bar{\nu}_{Le}\left(1+U_S\right)\not{\partial}\nu_{Le} - \frac{1}{2}\bar{\nu}_{Le} m_\nu \nu^c_{Le} + \text{H.c.} \tag{11}$$

Here U_S is a real number mediated by the vector-like fermion while m_ν is the neutrino mass suppressed by the right-handed neutrinos. We have

$$U_S = f_S \frac{v_\eta^2}{2m_S^2} f_S^\dagger\,, \quad m_\nu = -y_N \frac{v_{\phi_e}^2}{2M_N} y_N^T\,. \tag{12}$$

We then should normalize the left-handed electron neutrino and its mass by

$$(1+U_S)^{\frac{1}{2}}\nu_{Le} \to \nu_{Le}\,, \quad (1+U_S)^{-\frac{1}{2}} m_\nu (1+U_S^T)^{-\frac{1}{2}} \to m_\nu\,. \tag{13}$$

In principle, the right-handed neutrinos will also modify the kinetic term of the left-handed electron neutrino. However, this contribution is of the order of m_ν/M_N and hence is negligible.

By integrating out the vector-like fermion, a term of $-x_S g_X \bar{\nu}_{Le} U_S \gamma_\mu \nu_{Le} X^\mu$ will be generated. The relevant diagram is shown in Fig. 1. Including the normalization according to Eq. (13), one finds the effective coupling of the electron neutrino ν_e to the X boson should be

$$\frac{\epsilon g_{Y'}\beta}{2}\bar{\nu}_e\gamma_\mu(1-\gamma_5)\nu_e X^\mu \to \frac{\epsilon g_{Y'}\beta}{2}\frac{1-\frac{g_X x_S}{\epsilon g_{Y'}\beta}U_S}{1+U_S}\bar{\nu}_e\gamma_\mu(1-\gamma_5)\nu_e X^\mu\,. \tag{14}$$

With an appropriate choice of parameters, the coupling of X to ν_e can be suppressed, even to zero if $g_X x_S U_S = \epsilon g_{Y'}\beta$. For example, taking $g_X x_S U_S = \epsilon g_{Y'}\beta$, $|12\epsilon g_{Y'}/e| = 0.002 \sim 0.01$, and $\beta = 0.14$, we then can have $g_X x_S U_S = 3.5\times 10^{-5} - 7.1\times 10^{-6}$ and hence $U_S^{\frac{1}{2}} = (2.7-5.9)\times 10^{-3}/(g_X^{\frac{1}{2}} x_S^{\frac{1}{2}})$. For a reasonable assumption $g_X x_S = \mathcal{O}(1)$, the parameter $U_S^{\frac{1}{2}}$ can be very small. This means a very small $\nu_L - S$ mixing as desired.

The discussions in Eqs. (10)–(14) can be generalized for all of the three generations by introducing more iso-doublet Higgs scalars and vector-like fermions with proper $U(1)'_Y \times U(1)_X$ charges. In this case, the numbers U_S and m_ν should be understood as a hermitian matrix and a symmetric matrix, respectively.

3. The fifth force

Combining Eqs. (8), (9) and (14), we derive the parameters ε^v_f in the effective theory (1) by

$$\varepsilon^v_u = -\frac{4\epsilon g_{Y'}}{e}\,, \quad \varepsilon^v_d = \frac{8\epsilon g_{Y'}}{e}\,, \quad \varepsilon^v_e = -\frac{\epsilon\beta g_{Y'}}{e}\,, \quad \varepsilon^v_{\nu_e} = \frac{\epsilon g_{Y'}\beta}{2e}\frac{1-g_X U_S/(\epsilon g_{Y'}\beta)}{1+U_S}\,. \tag{15}$$

Since, $\varepsilon^v_p = 2\varepsilon^v_u + \varepsilon^v_d = 0$, the vector current interaction of the X boson is protophobic type as proposed in Ref. [4]. At this moment, one may have naively concluded that they can easily fit the required numbers for explaining the $^8Be^* \to {}^8Be\, e^+e^-$ data as given in Eqs. (4). However, the model above also contains axial-vector current interactions (6) with

$$\varepsilon^a_u = -\frac{6\epsilon g_{Y'}}{e}\,, \quad \varepsilon^a_d = \frac{6\epsilon g_{Y'}}{e}\,, \quad \varepsilon^a_e = 0\,, \quad \varepsilon^a_{\nu_e} = -\frac{\epsilon g_{Y'}\beta}{2e}\frac{1-g_X U_S/(\epsilon g_{Y'}\beta)}{1+U_S}\,. \tag{16}$$

Therefore the model is actually protophobic only in the vector current interactions.

It is necessary to check if the axial-vector current interactions can satisfy the experimental data. Remarkably, the axial-vector current interactions between the X boson and the u and d quarks are proportional to $\varepsilon^a_u \bar{u}\gamma^\mu\gamma_5 u + \varepsilon^a_d \bar{d}\gamma^\mu\gamma_5 d$ which now is the sum of a zero iso-scalar current $[(\varepsilon^a_u + \varepsilon^a_d)/2](\bar{u}\gamma^\mu\gamma_5 u + \bar{d}\gamma^\mu\gamma_5 d) \equiv 0$ and a nonzero iso-vector current $[(\varepsilon^a_u - \varepsilon^a_d)/2](\bar{u}\gamma^\mu\gamma_5 u - \bar{d}\gamma^\mu\gamma_5 d) \not\equiv 0$ [11]. If one just considers iso-scalar induced $^8Be^* \to {}^8BeX$ process, iso-vector currents does not enter. The iso-vector interaction may induce $^8B^{*\prime}_e \to {}^8B_eX$. As have mentioned before that the absence of new particle creation in the $^8B^{*'}_e$ decay has been suggested to be due to kinematical suppression [4]. There may be also other physical effects, such as $\pi^0 \to e^+e^-$. However, the electron only has a vector current interaction with the X boson so that the contribution from our model to $\pi^0 \to e^+e^-$ can be identically zero. No constraint can be obtained from the above considerations.

The protophobic nature in the vector current interactions of the X boson results in an interaction term $\pi^0\tilde{X}_{\mu\nu}F^{\mu\nu}$ through triangle anomaly diagram which generates $\pi^0 \to \gamma\gamma$ decay. Here $F^{\mu\nu}$ is the photon field strength. Experimental limit on search of $\pi^0 \to X\gamma$ constrains the interaction to be protophobic as mentioned earlier. Our model contains the axial-vector current couplings of the X boson to the u and d quarks. Naively, one would expect the emergence of an interaction term of the type of $\pi^0 X_{\mu\nu}F^{\mu\nu}$ which affects the result. However, this term does not appear since it violates CP and is therefore forbidden. The analysis of $\pi^0 \to X\gamma$ in Ref. [4] still hold in our model. To explain the observed anomalous ^8Be nuclear transitions and fulfill all of the other experimental limits, one needs $|\varepsilon^v_n| = |12\epsilon g_{Y'}/e|$ to be in the range $0.002 \sim 0.01$ which results in a range $(0.5 \sim 2.6) \times 10^{-4}$ for $|\varepsilon g_{Y'}|$.

There are also direct constraints on axial current interaction from parity violation data in e-quark scattering. The quantities which are probed in this type of scattering are sensitive to the parameters C_{if} defined by

$$L_{PV} = \frac{G_F}{\sqrt{2}}(C_{1f}\bar{e}\gamma^\mu\gamma_5 e\bar{f}\gamma_\mu f + C_{2f}\bar{e}\gamma^\mu e\bar{f}\gamma_\mu\gamma_5 f)\,, \tag{17}$$

where $C_{1f} = 2g^e_A g^f_V$ and $C_{2f} = 2g^e_V g^f_A$. In the SM $g^f_V = (T^3_f - 2Q_f \sin^2\theta_W)$ and $g^f_A = T^3_f$. T^3_f takes values $+1/2$ for up type of quarks and $-1/2$ for an electron. θ_W is the Weinberg angle.

One of the most sensitive measurements is obtained by PVDIS experiment carried out at $\langle Q^2\rangle = 1.085$ GeV^2 and $\langle Q^2\rangle = 1.901$ GeV^2 [12]. Combined with results from other experimental data [7] results in $2C_{2u} - C_{2d} = -0.145 \pm 0.086$. This is consistent with SM prediction of -0.095, but the central values do not coincide. The introduction of X boson will modify $g^i_{V,A}$. In our model, $g^e_A = 0$, so only C_{2f} will be modified. Normalizing to the SM contributions, we have

$$2C_{2u} - C_{2d} = 3\left(-\frac{1}{2} + 2\sin^2\theta_W\right)\left(1 + \frac{m_Z^2}{\langle Q^2\rangle}\frac{16\sin^2\theta_W\cos^2\theta_W\varepsilon^v_e\varepsilon^a_u}{1-4\sin^2\theta_W}\right). \tag{18}$$

Using $\sin^2\theta_W = 0.0234$ [12], a conservative $\langle Q^2\rangle = 1.085$ GeV^2 and the fact that $\varepsilon^v_n = -2\epsilon^a_u$, we obtain

$$2C_{2u} - C_{2d} = -0.095\left(1 - 1.7\frac{\varepsilon^v_e}{10^{-3}}\frac{\varepsilon^v_n}{10^{-2}}\right). \tag{19}$$

To produce the experimental central value for $2C_{2u} - C_{2d}$, $\varepsilon^v_e\varepsilon^v_n$ needs to be -0.3×10^{-5}. If one keeps as large a ε^v_n close to its upper bound, ϵ^v_e needs to be -0.21×10^{-3}. This is within the allowed range, but may not be a good choice for alleviating the muon g-2 anomaly problem. One may want to choose as large a number for ε^v_e as possible, 1.4×10^{-3}. In that case, ε^v_n becomes 0.3×10^{-2} which is again within the allowed range to solve the anomaly in $^8Be^* \to {}^8Be\, e^+e^-$. If one allows $2C_{2u} - C_{2d}$ to reach its 1σ upper bound and keep ε^v_e as large a possible, ε^v_n can also reach its upper bound of 0.006, which is again within the allowed range.

4. Other implications

Since in our model, the first two generations of charged fermions couple to the X boson with a same strength, in particular, $\varepsilon^v_d = \varepsilon^v_s = 2\varepsilon^v_n/3$, there may be constraints from data on X production from other quarks. The allowed upper value for $|\varepsilon^v_s| = 0.0073$ is at tension with the boundary of the 90% c.l. allowed region from KLOE data [13] on $\phi \to \eta X$. But allowed at 3σ c.l. Improved data can test the model further. However, if one takes ε^v_n to be about 0.6×10^{-2} there is no problem for ε^v_s.

Furthermore, we have $|\varepsilon^v_\mu| = |\varepsilon^v_e|$, which has an effect on $(g-2)_\mu$. One can calculate the X boson contribution to Δa_μ which has a 3σ deviation, $\Delta a_\mu = 288(80)\times10^{-11}$ [14]. Using the 3σ upper bound of $\varepsilon^v_e = 1.4\times10^{-3}$ ($\beta = 0.14$), we obtain $\Delta a_\mu = 152\times10^{-11}$ from the X boson contribution which improves the deviation to 1.5σ. A smaller value for ε^v_e is not favored from muon $g-2$ anomaly problem consideration.

We now discuss possible ways to further test the model. Besides continuing similar experiments with higher sensitivity for those already provided constraints, it would be good to find new ways for testing the model. One may carry out $e^+e^- \to \gamma X$ followed by measuring e^+e^- with a center of mass energy $\sqrt{s}$ at BES III and also at BELLE II. Since in our model ε^v_e is constrained to be less than 1.4×10^{-3}, the cross section is typically less than 10^{-2} fb which may be too small to be measured experimentally in the near future. At hadron collider because $|\varepsilon^v_d|$ is as large as 7×10^{-3}, the cross section for, $pp \to \gamma X +$ jets, may be larger. However, in the hadronic back ground the measurement will be very challenging.

Exclusive decay of a meson A to BX followed by measuring e^+e^- from on-shell X decay may be very hopeful. If the initial state A is a state with two constituent quarks (a quark with an anti-quark have the same absolute electric charge $|Q_q|$), one then obtains, for the vector part of the current interaction. $R(X/\gamma, Q_q) = Br(A \to BX)_{Q_q}/Br(A \to B\gamma)_{Q_q} = (\varepsilon^v_q/Q_q)^2$. Assuming $X \to e^+e^-$ saturating the X decay, for $Q_q = 2/3$ and $Q_q = -1/3$, we have, respectively

$R(X/\gamma,\ 2/3) = \left|\frac{1}{2}\varepsilon_n^v\right|^2 \approx 3.0 \times 10^{-5}$ and $R(X/\gamma,\ -1/3) = \left|2\varepsilon_n^v\right|^2 \approx 4.8 \times 10^{-4}$. When axial current contributions are included which will add terms proportional to $|\epsilon_q^a|^2$, ratios become larger. So the numbers 3.0×10^{-5} and 4.8×10^{-4} represent lower bounds for the ratios.

The above bounds can be used to study radiative (X boson) decays of the vector mesons J/ψ into a spin zero meson, or radiative (X boson) decays of the flavored vector mesons D^{*0} into a spin zero meson. We find the most promising decay mode is $D^{*0} \to D^0 X \to D^0 e^+e^-$ for the reasons that $D^{*0} \to D^0\gamma$ has a large branching ratio $(38.1 \pm 2.9)\%$ [7] and a large number of this decay can be copiously produced and studied at the LHCb. At the LHC run III, the LHCb may have an integrated luminosity of $15\,\mathrm{fb}^{-1}$ which means that the event number for $D^{*0} \to D^0\gamma$ can reach about 5×10^{12}. The analysis for constraining $\varepsilon_c^v = -\varepsilon_n^v/3$ is similar to that carried out for constraining the dark photon mixing parameter in Ref. [15] where it was shown that for $m_X \simeq 17\,\mathrm{MeV}$ the LHCb sensitivity for the mixing parameter can reach about 2.4×10^{-5} with an integrated luminosity of $15\,\mathrm{fb}^{-1}$. Normalizing their notation to ours, the sensitivity for $|\varepsilon_c^v|$ can be 1.6×10^{-5}. Our model can be tested at the LHCb.

In the above discussions, the third generation fermions do not have interaction with X boson. However, it may turn out that the third generation quarks interact with X boson, but the second generation does not. In this case, the above formulae can be used to study radiative (X boson) decays of the vector mesons Υ into a spin zero meson, or radiative (X boson) decays of the flavored vector mesons B_d^{*0} and B_s^{*0} into a spin zero meson.

5. Conclusions

In summary, we have proposed a realistic gauge anomaly free model with a $17\,\mathrm{MeV}$ X gauge boson mediating a fifth force to explain the anomaly reported ${}^8Be^* \to {}^8Be\, e^+e^-$. The X boson comes from extension of the SM with two additional U(1) gauge symmetries producing a protophobic pure vector current interaction with quarks. Although the axial-vector current interactions are strongly constrained by the measurement of parity violation in e-quark scattering, their contributions cancel out in the iso-scalar interaction for ${}^8Be^* \to {}^8BeX$. Furthermore, the model allows us to suppress the unexpected couplings of the X boson to the electron neutrino. Within the allowed parameter space, the model may be able to alleviate the anomaly in $(g-2)_\mu$. The X boson also couples to the second-generation quarks and hence may induce $D^{*0} \to D^0 X \to D^0\, e^+e^-$ or $B_{d,s}^{*0} \to B_{d,s}^0 X \to B_{d,s}^0\, e^+e^-$ which can be studied at the LHCb to probe the parameter space for explaining ${}^8Be^* \to BeX \to Be\, e^+e^-$. For generating the required fermion masses, we need introduce multi iso-doublet scalars carrying different $U(1)_{Y'}$ and/or $U(1)_X$ charges. This means rich flavor changing phenomena including the anomaly in $h \to \mu\tau$ from the LHC and the anomalies in $b \to s\mu^+\mu^-$ transitions shown in experimental data. The parameter space allows the existence of decoupling limit, that is, the SM like Higgs, is the only light particle and the rest to be much heavier an leave little traces experimentally. But it may happen that observable effects show up at accessible level. We will present detailed studies elsewhere.

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