Explanation of the 17 MeV Atomki Anomaly in a $U(1)'$-Extended 2-Higgs Doublet Model

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Motivated by an anomaly observed in the decay of an excited state of Beryllium (^{8}Be) by the Atomki collaboration, we study an extension of the Standard Model with a gauged $U(1)'$ symmetry in presence of a 2-Higgs Doublet Model structure of the Higgs sector. We show that this scenario complies with a variety of experimental results and is able to explain the potential presence of a resonant spin-1 gauge boson, Z', with a mass of 17 MeV in the Atomki experimental data, for appropriate choices of $U(1)'$ charges and Yukawa interactions.

The Atomki pair spectrometer experiment [1] was set up for searching e^+e^- internal pair creation in the decay of excited ^{8}Be nuclei (henceforth, ^{8}Be*), the latter being produced with the help of a beam of protons directed on a Lithium (^{7}Li) target. The proton beam was tuned in such a way that the different ^{8}Be excitations could be separated with high accuracy.

In the data collection stage, a clear anomaly was observed in the decay of ^{8}Be* with spin-parity $J^P = 1^+$ into the ground state ^{8}Be with spin-parity 0^+ (both with isospin $T = 0$), where ^{8}Be* had an excitation energy of 18.15 MeV. Upon analysis of the electron-positron properties, the spectra of both their opening angle θ and invariant mass M presented the characteristics of an excess consistent with an intermediate boson X being produced on-shell in the decay of the ^{8}Be* state, with the X object subsequently decaying into e^+e^- pairs. The best fit to the mass M_X of X was given as [1] $M_X = 16.7 \pm 0.35$ (stat) ± 0.5 (sys) MeV, in correspondence of a ratio of Branching Ratios (BRs) obtained as

$$\frac{\mathrm{BR}(^8\mathrm{Be}^* \to X + {}^8\mathrm{Be})}{\mathrm{BR}(^8\mathrm{Be}^* \to \gamma + {}^8\mathrm{Be})} \times \mathrm{BR}(X \to e^+e^-) = 5.8 \times 10^{-6}.$$

This combination yields a statistical significance of the excess of about $6.8\,\sigma$ [1].

An explanation of the X nature was attempted by [2, 3], in the form of models featuring a new vector boson Z' with a mass $M_{Z'}$ of about 17 MeV, with vector-like couplings to quarks and leptons. Constraints on such a new state, notably from searches for $\pi^0 \to Z' + \gamma$ by the NA48/2 experiment [4], require the couplings of the Z' to up and down quarks to be 'protophobic', i.e., that the charges $e\epsilon_u$ and $e\epsilon_d$ of up and down quarks – written as multiples of the positron charge e – satisfy the relation $2\epsilon_u + \epsilon_d \lesssim 10^{-3}$ [2, 3]. Subsequently, further studies of such models have been performed in [5–12][1].

In the footsteps of this literature, we consider here an extension of the SM described by a generic $U(1)'$ group. Due to the presence of two such Abelian symmetries, $U(1)_Y \times U(1)'$, the most general kinetic Lagrangian of the corresponding fields, $\hat{B}_\mu$ and $\hat{B}'_\mu$, respectively, allows for a gauge invariant mixing of the two field-strengths

$$\mathcal{L}_{\mathrm{kin}} = -\frac{1}{4}\hat{F}_{\mu\nu}\hat{F}^{\mu\nu} - \frac{1}{4}\hat{F}'_{\mu\nu}\hat{F}'^{\mu\nu} - \frac{\kappa}{2}\hat{F}'_{\mu\nu}\hat{F}^{\mu\nu}, \quad (1)$$

where κ is the kinetic mixing parameter between $U(1)_Y$ and $U(1)'$. A diagonal form for this Lagrangian can be obtained by transformation of the Abelian fields such that the gauge covariant derivative becomes

$$\mathcal{D}_\mu = \partial_\mu + ... + ig_1 Y B_\mu + i(\tilde{g}Y + g'z)B'_\mu, \quad (2)$$

where Y and z are the hypercharge and $U(1)'$ charge, respectively, and $\tilde{g}$ the gauge coupling mixing between the two Abelian groups.

We also consider the presence of two $SU(2)$ (pseudo)scalar doublets, embedded in a 2-Higgs Doublet Model (2HDM) scalar potential, Φ_1 and Φ_2, with the same hypercharge $Y = 1/2$ and two different charges z_{Φ_1} and z_{Φ_2} under the extra $U(1)'$. The new Abelian symmetry replaces the discrete Z_2 one usually imposed in 2HDMs to avoid tree-level flavour changing neutral currents [14, 15]. Alongside spontaneous Electro-Weak Symmetry Breaking (EWSB) of the SM gauge symmetry through the Vacuum Expectation Values (VEVs) of the two Higgs doublets $\langle\Phi_{1,2}\rangle = v_{1,2}$, with $v^2 = v_1^2 + v_2^2$ and $\tan\beta = v_2/v_1$, one may in principle also have a contribution to $U(1)'$ symmetry breaking through the VEV $\langle\chi\rangle = v'$ of an extra SM-singlet scalar χ, indeed connected to the mass term $m_{B'} = g'z_\chi v'$. The diagonalisation of the mass matrix of neutral gauge bosons implies

[1] An alternative explanation was given in [13], wherein the X was identified with a light pseudoscalar state with couplings to up and down type quarks about 0.3 times those of the Standard Model (SM) Higgs boson.

	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)'$
Q_L	3	2	1/6	z_Q
u_R	3	1	2/3	z_u
d_R	3	1	-1/3	$2z_Q - z_u$
L	1	2	-1/2	$-3z_Q$
e_R	1	1	-1	$-2z_Q - z_u$
s_i	1	1	0	z_{s_i}

TABLE I. Flavour universal charge assignment in the $U(1)'$ extension of the SM.

the following mixing angle, θ', between the SM Z and new Z':

$$\tan 2\theta' = \frac{2\bar{g}_\Phi g_Z}{\bar{k}^2 + 4m_{B'}^2/v^2 - g_Z^2}, \tag{3}$$

where $g_Z = \sqrt{g_1^2 + g_2^2}$ is the EW coupling. The parameters $\bar{g}_\Phi$ and $\bar{k}^2$ are defined as $\bar{g}_\Phi = \bar{g}_{\Phi_1}\cos^2\beta + \bar{g}_{\Phi_2}\sin^2\beta$ and $\bar{k}^2 = \bar{g}_{\Phi_1}^2\cos^2\beta + \bar{g}_{\Phi_2}^2\sin^2\beta$, where we have introduced the couplings $\bar{g}_{\Phi_n} = \tilde{g} + 2g' z_{\Phi_n}$ with $n = 1, 2$ inherited from the interactions of the 2HDM (pseudo)scalars with the Z'. The masses of the Z and Z' gauge bosons are

$$M_{Z,Z'} = g_Z \frac{v}{2}\left[\frac{1}{2}\left(\frac{\bar{k}^2 + 4m_{B'}^2/v^2}{g_Z^2} + 1\right) \mp \frac{\bar{g}_\Phi}{\sin 2\theta'\, g_Z}\right]^{\frac{1}{2}} \tag{4}$$

and, for $g', \tilde{g} \ll 1$ and $m_{B'}^2 \ll v^2$, the Z' mass is given by

$$M_{Z'}^2 \simeq m_{B'}^2 + \frac{v^2}{4} g'^2 (z_{\Phi_1} - z_{\Phi_2})^2 \sin^2(2\beta), \tag{5}$$

which is non-vanishing even when $m_{B'} \to 0$ due to a possible split between z_{Φ_1} and z_{Φ_2}. In the $m_{B'} \simeq 0$ limit one finds, for $M_{Z'} \simeq 17$ MeV and $v \simeq 246$ GeV, $g' \sim 10^{-4}$. Here, two comments are in order. Firstly, in case of one Higgs doublet, the limit $m_{B'} \ll v$ leads to $M_Z' \simeq m_{B'}$ and the SM Higgs sector does not play any role. Secondly, in the 2HDM case with $z_{\Phi_1} \neq z_{\Phi_2}$, the symmetry breaking of the $U(1)'$ can actually be realised without the extra SM-singlet χ. In this scenario, which we adopt here, the typical CP-odd state of the 2HDM extensions represents the longitudinal degree of freedom of the Z'.

The conditions required by the cancellation of gauge and gravitational anomalies, which strongly constrain the charge assignment of the SM spectrum under the extra $U(1)'$ gauge symmetry, are here imposed. This implies the introduction of SM-singlet fermions, s_i, which could be exploited for implementing a seesaw mechanism generating light neutrino masses. The charge assignments of the spectrum in our extension of the SM are given in Tab. I, where the z_{s_i}'s are chosen to cancel the anomaly in the $U(1)'U(1)'U(1)'$ and $U(1)'GG$ triangle diagrams, G being the gravitational current.

The interactions between the SM fermions and the Z' gauge boson are described by the corresponding Lagrangian, $\mathcal{L}_{\rm int} = -J^\mu_{Z'} Z'_\mu$, where the gauge current is given by

$$J^\mu_{Z'} = \sum_f \bar{\psi}_f \gamma^\mu \left(C_{f,L} P_L + C_{f,R} P_R\right)\psi_f \tag{6}$$

with coefficients

$$\begin{aligned} C_{f,L} &= -g_Z s'\left(T_f^3 - s_W^2 Q_f\right) + \bar{g}_{f,L}\, c'\,, \\ C_{f,R} &= g_Z s_W^2 s' Q_f + \bar{g}_{f,R}\, c'\,. \end{aligned} \tag{7}$$

In these equations we have adopted the shorthand notations $s_W \equiv \sin\theta_W$, $c_W \equiv \cos\theta_W$, $s' \equiv \sin\theta'$ and $c' \equiv \cos\theta'$. We also have defined $\bar{g}_{f,L/R} = \tilde{g} Y_{f,L/R} + g' z_{f,L/R}$ with Y_f the hypercharge, z_f the $U(1)'$ charge, T_f^3 the third component of the weak isospin and Q_f the electric charge of a generic fermion f. Analogously, the vector and axial-vector components of the Z' interactions are

$$\begin{aligned} C_{f,V} &= \frac{C_{f,R} + C_{f,L}}{2} = \frac{1}{2}\left[-g_Z s'(T_f^3 - 2s_W^2 Q_f) + c'\tilde{g}(2Q_f - T_f^3) + c' g'(z_{f,L} + z_{f,R})\right]\,, \\ C_{f,A} &= \frac{C_{f,R} - C_{f,L}}{2} = \frac{1}{2}\left[(g_Z s' + \tilde{g} c') T_f^3 - c' g'(z_{f,L} - z_{f,R})\right]\,, \end{aligned} \tag{8}$$

where we have exploited the relation $Y_f = Q_f - T_f^3$ and used the definition of $\bar{g}_{f,L/R}$. These equations can considerably be simplified by realising that $g_Z s'$ is of the same order of $\tilde{g}$ for $g', \tilde{g} \ll 1$, which leads to

$$\begin{aligned} C_{f,V} &\simeq \tilde{g} c_W^2\, Q_f + g'\left[z_\Phi(T_f^3 - 2s_W^2 Q_f) + z_{f,V}\right]\,, \\ C_{f,A} &\simeq g'\left[-z_\Phi\, T_f^3 + z_{f,A}\right], \end{aligned} \tag{9}$$

where we have introduced the vector and axial-vector $U(1)'$ charges $z_{f,V/A} = 1/2(z_{f,R} \pm z_{f,A})$. Notice that z_Φ can be either z_H for a single Higgs doublet model or $z_{\Phi_1}\cos^2\beta + z_{\Phi_2}\sin^2\beta$ for a 2HDM. The Z' couplings are characterised by the sum of three different contributions. The kinetic mixing $\tilde{g}$ induces a vector-like term proportional to the Electro-Magnetic (EM) current which is the only source of interactions when all the SM fields are neutral under $U(1)'$. In this case the Z' is commonly dubbed *dark photon*. The second term is induced by z_Φ, the $U(1)'$ charge in the Higgs sector, and leads to a *dark Z*, namely a gauge boson mixing with the SM Z boson. Finally, there is the standard gauge interaction proportional to the fermionic $U(1)'$ charges $z_{f,V/A}$.

We can now delineate two different scenarios depending on the structure of the axial-vector couplings of the Z' boson. In particular, when only a $SU(2)$ doublet is taken into account, the $C_{f,A}$ coefficients are suppressed with respect to the vector-like counterparts (see [16]). This is a direct consequence of the gauge invariance of the Yukawa interactions which forces the $U(1)'$ charge of the Higgs field to satisfy the conditions $z_H = z_Q - z_d = -z_Q + z_u = z_L - z_e$. Inserting the previous relations into Eq. (9), we find $C_{f,A} \simeq 0$, which describes a Z' with only vector interactions with charged leptons and quarks. We stress again that the suppression of the axial-vector coupling is only due to the structure of the scalar sector, which envisions only one $SU(2)$ doublet, and to the gauge invariance of the Yukawa Lagrangian. This feature is completely unrelated to the $U(1)'$ charge assignment of the fermions, the requirement of anomaly cancellation and the matter content potentially needed to account for it. In the scenario characterised by two Higgs doublets, the axial-vector couplings of the Z' are, in general, of the same order of magnitude as the vector ones and the cancellation between the two terms of $C_{f,A}$ in Eq.(9) is not achieved regardless of the details of the Yukawa Lagrangian, namely, of the type of the 2HDM considered. Notice that, unlike the pure vector-like case, it is extremely intricate to build up a model of a Z' with only axial-vector interactions and, in general, both C_V and C_A are present.

A well-known realisation of the scalar sector with two Higgs doublets is the so-called type-II in which the up-type quarks couple to one Higgs doublet (conventionally chosen to be Φ_2) while the down-type quarks couple to the other (Φ_1). The anomaly cancellation condition arising from the $U(1)'SU(3)SU(3)$ diagram and the gauge invariance of the Yukawa Lagrangian require $2z_Q - z_d - z_u = z_{\Phi_1} - z_{\Phi_2} = 0$, which necessarily calls for extra coloured states when $z_{\Phi_1} \neq z_{\Phi_2}$. These new states must be vector-like under the SM gauge group and chiral under the extra $U(1)'$ [16].

A far more interesting scenario is realised when the scalar sector reproduces the structure of the type-I 2HDM in which only one (Φ_2) of the two Higgs doublets participates in the Yukawa interactions. The corresponding Lagrangian is the same as the SM one and its gauge invariance simply requires $z_{\Phi_2} = -z_Q + z_u = z_Q - z_d = z_L - z_e$, without constraining the $U(1)'$ charge of Φ_1. Differently from the type-II scenario in which extra coloured states are required to build an anomaly-free model, in the type-I case the UV consistency of the theory can be easily satisfied introducing only SM-singlet fermions as demanded by the anomaly cancellation conditions of the $U(1)'U(1)'U(1)'$ and $U(1)'GG$ correlators. Nevertheless, the mismatch between z_Φ and $z_{f,A} = \pm z_{\Phi_2}/2$ (for up-type and down-type quarks, respectively) prevents $C_{f,A}$ to be suppressed and the Z' interactions are given by

$$
\begin{aligned}
C_{u,V} &= \frac{2}{3}\tilde{g}c_W^2 + g'\left[z_\Phi\left(\frac{1}{2} - \frac{4}{3}s_W^2\right) + z_{u,V}\right], \\
C_{u,A} &= -\frac{g'}{2}\cos^2\beta(z_{\Phi_1} - z_{\Phi_2}), \\
C_{d,V} &= -\frac{1}{3}\tilde{g}c_W^2 + g'\left[z_\Phi\left(-\frac{1}{2} + \frac{2}{3}s_W^2\right) + z_{d,V}\right], \\
C_{d,A} &= \frac{g'}{2}\cos^2\beta(z_{\Phi_1} - z_{\Phi_2}), \\
C_{e,V} &= -\tilde{g}c_W^2 + g'\left[z_\Phi\left(-\frac{1}{2} + 2s_W^2\right) + z_{e,V}\right], \\
C_{e,A} &= \frac{g'}{2}\cos^2\beta(z_{\Phi_1} - z_{\Phi_2}), \\
C_{\nu,V} &= -C_{\nu,A} = \frac{g'}{2}(z_\Phi + z_L). \qquad (10)
\end{aligned}
$$

We now show that the structure of the couplings discussed above is able to explain the presence of a Z' resonance in the $^8\mathrm{Be}^*$ decay. As pointed out in [3], the contribution of the axial-vector couplings to the $^8\mathrm{Be}^* \to {}^8\mathrm{Be}\, Z'$ decay is proportional to $k/M_{Z'} \ll 1$, where k is the momentum of the Z', while the vector component is suppressed by $k^3/M_{Z'}^3$. Therefore, in our case, being $C_{f,V} \sim C_{f,A}$, we can neglect the effects of the vector couplings of the Z' and their interference with the axial counterparts. The relevant matrix elements for the $^8\mathrm{Be}^*$ transition mediated by an axial-vector boson have been computed in [17]. Notice that the axial couplings of the quarks and, therefore, the width of the $^8\mathrm{Be}^* \to {}^8\mathrm{Be}\, Z'$ decay are solely controlled by the product $g'\cos^2\beta$ while the kinetic mixing $\tilde{g}$ only affects the BR$(Z' \to e^+e^-)$ since the $Z' \to \nu\nu$ decay modes are allowed (we assume that the $Z' \to s_i s_j$ decays are kinematically closed). For definiteness, we consider a $U(1)_{\mathrm{dark}}$ charge assignment with $z_f = 0$ and $z_{\Phi_2} = 0$ and we choose $z_{\Phi_2} = 1$ and $\tan\beta = 1$. Analogue results may be obtained for different $U(1)'$ charge assignments and values of $\tan\beta$. We show in Fig. 1 the parameter space explaining the Atomki anomaly together with the most constraining experimental results. The orange region, where the Z' gauge couplings comply with the best-fit of the $^8\mathrm{Be}^*$ decay rate in the mass range $M_{Z'} = 16.7\,\mathrm{MeV} - 17.6\,\mathrm{MeV}$ [1, 3], encompasses the uncertainties on the computation of the nuclear matrix elements [17]. The region above it is excluded by the non-observation of the same transition in the isovector excitation $^8\mathrm{Be}^{*\prime}$ [1]. The horizontal grey band selects the values of g' accounting for the Z' mass in the negligible $m_{B'}$ case in which the $U(1)'$ symmetry breaking is driven by the two Higgs doublets. Furthermore, among all other experimental constraints involving a light Z' that may be relevant for this analysis we have shown the most restrictive ones. The parity-violating Møller scattering measured at the SLAC E158 experiment [18] imposes a constraint on the product $C_{e,V}C_{e,A}$ of the Z', namely $|C_{e,V}C_{e,A}| \lesssim 10^{-8}$ for $M_{Z'} \simeq 17$ MeV

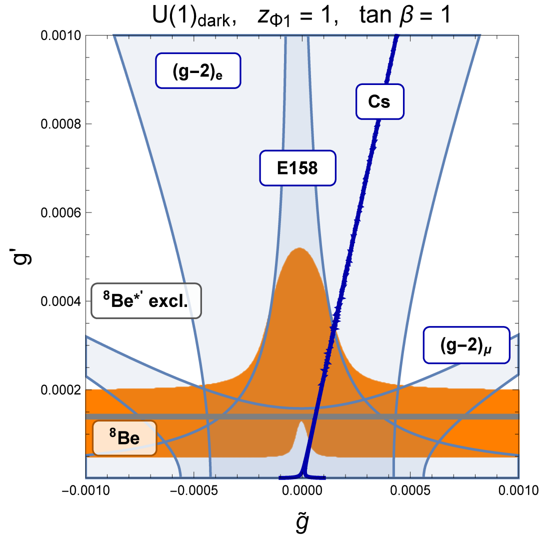

FIG. 1. Allowed parameter space explaining the anomalous ^{8}Be* decay.

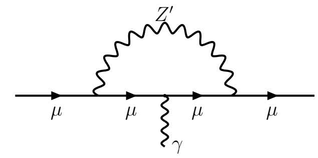

FIG. 2. The new contribution to the muon anomalous magnetic moment in a $U(1)'$ extension of the SM.

[16]. The strongest bound comes from the atomic parity violation in Cesium (Cs), namely from the measurement of its weak nuclear charge ΔQ_W [19, 20], which requires $|\Delta Q_W| \lesssim 0.71$ at 2σ [21]. It represents a constraint on the product of $C_{e,A}$ and a combination of $C_{u,V}$ and $C_{d,V}$. This bound can be avoided if the Z' has either only vector or axial-vector couplings but in a general scenario it imposes severe constraints on the gauge couplings $g', \tilde{g}$. The light-boson contribution to the anomalous magnetic moment of the electron has also been taken into account, as it is required to be within the 2σ uncertainty of the departure of the SM prediction from the experimental result [22]. We now analyse the contribution of a very light gauge boson Z' to the muon anomalous magnetic moment which has been measured at Brookhaven National Laboratory to a precision of 0.54 parts per million. The current average of the experimental results is given by [23, 24]

$$a_\mu^{\rm exp} = 11659208.9(6.3) \times 10^{-10}, \tag{11}$$

which is different from the SM prediction by 3.3σ to 3.6σ: $\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (28.3 \pm 8.7 \text{ to } 28.7 \pm 8.0) \times 10^{-10}$. From the interaction Lagrangian described above one finds a new contribution to $(g-2)_\mu$ generated by a one-loop diagram with Z' exchange as shown in Fig. 2, which leads to

$$\delta a_\mu^{Z'} = \frac{r_{m_\mu}}{4\pi^2} \left[C_{\mu,V}^2 \, g_V(r_{m_\mu}) - C_{\mu,A}^2 \, g_A(r_{m_\mu}) \right], \tag{12}$$

where $r_{m_\mu} \equiv (m_\mu / M_{Z'})^2$ and g_V, g_A are given by

$$g_V(r) = \int_0^1 dz \frac{z^2(1-z)}{1-z+rz^2}, \tag{13}$$

$$g_A(r) = \int_0^1 dz \frac{(z-z^2)(4-z)+2rz^3}{1-z+rz^2}. \tag{14}$$

For $M_{Z'} \simeq 17$ MeV one finds $\delta a_\mu^{Z'} \simeq 0.009 \, C_{\mu,V}^2 - C_{\mu,A}^2$. We require again that the contribution of the Z' to $(g-2)_\mu$, which is mainly due to its axial-vector component, is less than the 2σ uncertainty of the discrepancy between the SM result and the experimental measure.

We finally comment on the constraints imposed by neutrino-electron scattering processes [25–27], the strongest one being from $\bar{\nu}_e e$ scattering at the TEXONO experiment [26], which affect a combination of $C_{e,V/A}$ and $C_{\nu,V}$. In the protophobic scenario, in which the Z' has only vector interactions, the constrained ν coupling to the Z' boson is in high tension with the measured ^{8}Be* decay rate since $C_{\nu,V} = -2C_{n,V}$, where $C_{n,V} = C_{u,V} + 2C_{d,V}$ is the coupling to neutrons, and a mechanism to suppress the neutrino coupling must be envisaged [3]. This bound is, in general, alleviated if the one attempts to explain the Atomki anomaly with a Z' boson with axial-vector interactions since the required gauge couplings $g', \tilde{g}$ are smaller than the ones needed in the protophobic case.

In summary, we have come to an exciting conclusion. The model that we have constructed, which minimally departs from the SM, in both the gauge sector (wherein a dark $U(1)'$ is added) and Higgs framework (wherein a second doublet is added with a type-I Yukawa configuration), with the two intertwined as it is the pseudoscalar state of the latter that spontaneously breaks the symmetry of the former, has the potential to explain the anomaly in the decays of the Beryllium. Notably, the ballpark of values of the g' coupling reproducing the ^{8}Be internal pair creation excess also predicts the mass of the Z' from EWSB and, therefore, as for the masses of the Z and W gauge bosons, the $M_{Z'} = 17$ MeV could be generated by the same EW mass scale $v \simeq 246$ GeV.

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