Resonant search for the $X_{17}$ boson at PADME

Luc Darmé, Marco Mancini, Enrico Nardi, and Mauro Raggi

I. INTRODUCTION

Nuclear excited states with typical energies up to several MeV can source in their transition to the ground state new light bosons with MeV masses. Searches for signals of new physics (NP) of this type are carried out for example at the ATOMKI Institute for Nuclear Research in Debrecen (HU), that recently reported an anomaly in the angular correlation spectra in $^8$Be and $^4$He nuclear transitions [1–3]. The excesses in both spectra can be interpreted as the production and subsequent decay into an $e^\pm$ pair of a new boson, that was named $X_{17}$ after the fitted value of its mass:

$$M_X = \begin{cases} 16.70 \pm 0.35 \pm 0.50 \text{ MeV} & (^8\text{Be} \ [1]) \\ 17.01 \pm 0.16 \text{ MeV} & (^8\text{Be} \ [2]) \\ 16.94 \pm 0.12 \pm 0.21 \text{ MeV} & (^4\text{He} \ [3]) \end{cases}$$

where in the first and third result the first error is statistical and the second is systematic. In order to reproduce the strength of the observed excess a significant coupling to the quarks is required, along with a coupling to $e^\pm$ sufficiently large to allow for the $X_{17} \to e^+e^-$ decays to occur within the ATOMKI apparatus. The nuclear data are not sufficient to fully determine the $X_{17}$ spin/parity quantum numbers [4–6], the most favourite possibilities being a vector or a pseudo-scalar particle.

The dominant constraints on a particle with such couplings arise from the process $\pi^0 \to \gamma X_{17}$ (followed by $X_{17} \to e^+e^-$) which has been thoroughly explored by the NA48/2 collaboration [7]. These constraints imply that the couplings of the $X_{17}$ to matter must include a certain amount of pion-phobia [5, 8, 9]. A large number of search strategies based primarily on the $X_{17}$-quark interactions have been put forward recently, however, in general they tend to suffer from a large model dependence [10–16]. Due to its electron/positron interactions the $X_{17}$ must abide with the standard search for “visible” dark photon, and strong lower bounds on its coupling to electrons arise in particular from the E141 [17–20] and Orsay [21, 22] experiments, and more recently from the results of the NA64 collaboration [23, 24]. The visible search from the KLOE experiment [25] finally gives an upper limit at the per-mil level for the coupling to electrons. Covering the remaining allowed parameter space can provide a definite answer regarding the NP origin of the anomaly, and various experimental proposals could probe this region in the future [26–28]. Additional strong indirect bounds can be also obtained under mild theoretical assumptions. In particular, requiring that in the UV limit the $X_{17}$ interactions respect weak $SU(2)$-invariance implies additional constraints, in particular from neutrinos measurements, see for instance Refs. [16, 29–32].

This paper is devoted to describe a dedicated search strategy for a light bosonic state with mass around 17 MeV, based on its production via resonant annihilation of positrons from the Frascati Beam Test Facility (BTF) [33] beam on atomic electrons in a fixed target $e^+e^- \to X_{17}$, with a subsequent prompt decay $X_{17} \to e^+e^-$. The importance of the resonant production process, and the possibility of exploiting it in fixed target experiments that exploit a primary positron beam, was first pointed out in Ref. [34]. The importance of this process was later recognised also for electron and proton beam dump experiments, where positrons are produced in electromagnetic showers as secondary particles, and led to re-analysis of old results, and improved projections for planned experiments [35–40].

Our search strategy relies on an upgraded version of the PADME (Positron Annihilation into Dark Matter Experiment) experiment [41, 42] currently running at the
Frascato National Laboratories (LNF). PADME exploits a positron beam from the DAΦNE LINAC accelerator in fixed target configuration with an active polycrystalline diamond target of 100 μm. We will discuss in Sec. II the $e^+e^- \rightarrow X_{17}$ production mechanism, followed by prompt $X_{17} \rightarrow e^+e^-$ decay. The planned Run III of PADME that will be dedicated to search for the $X_{17}$ is described in Sec. III. A quantitative study of the expected sources of background is presented in Sec. IV, and in Sec. V is used to infer projected limits.

II. RESONANT $X_{17}$ PRODUCTION

Let us first consider the case where $X_{17}$ is a spin-1 boson, which interacts with the Standard Model via the following Lagrangian:

$$L^{\text{Vect.}} \supset \sum_{f = e, u, d} X_{17}^{\mu} f \gamma_{\mu} (g_{\nu f} + \gamma^5 g_{\nu f}) f.$$

(2)

All the relevant processes considered in this work are proportional to the coupling combination $(g_{\nu e}^2 + g_{\nu e}^2)$, up to terms involving the ratio $m_{\text{ec}}^2/M_X^2 < 10^{-3}$ which will be neglected in the following. The dominant production mechanism for the $X_{17}$ boson in the PADME experiment (regardless of its parity and spin nature) is from the “resonant” process $e^+e^- \rightarrow X_{17}$. For high-energy positrons impinging on the target electrons taken to be at rest,1 the resonant condition reads

$$E_{\text{res}} = \frac{M_X^2}{2m_e}.$$

(3)

We assume that the positron energies $E_+$ have a Gaussian distribution with central value $E$ and spread $\sigma_E$:

$$f(E_+, E) = \frac{1}{\sqrt{2\pi}\sigma_E} e^{-\frac{(E_+ - E)^2}{2\sigma_E^2}}.$$

(4)

We will work under the assumption that the energy distribution of the positrons in the beam can be considered continuous when compared to the $X_{17}$ width $\Gamma_X$, which implies the requirement:

$$\frac{\Gamma_X M_X}{2m_e} \frac{1}{\sigma_E} N_{\text{tot}}(E) \sim \left( \frac{N_{\text{tot}}(E)}{1.1\times10^5} \right) \left( \frac{g_{ve}}{2 \times 10^{-4}} \right)^2 \gg 1,$$

(5)

where for simplicity of notations in the case of electron couplings we have defined $g_{ve} \equiv \sqrt{g_{\nu e}^2 + g_{\nu e}^2}$.

Eq. (5) $N_{\text{tot}}(E)$ is the total number of positrons in the beam with nominal energy $E$, and the strong inequality holds for $\sigma_E \sim O(1)$ MeV.

At the leading order in QED, the resonant cross-section for production of a vector $X_{17}$ is given by:

$$\sigma_{\text{res}}^{\text{Vec.}} = \frac{g_{ve}^2 \pi}{2m_e} \delta(E_+ - E_{\text{res}}).$$

(6)

The final number of $X_{17}$ produced per positron-on-target for a given beam energy $E$ is thus given by

$$N_{X_{17}}^{\text{per poT}}(E) = \frac{N_A Z\rho \ell_{\text{tar}} g_{ve}^2 \pi}{A} f(E_{\text{res}}, E).$$

(7)

where $\ell_{\text{tar}}$ and $\rho$ are respectively the target thickness and mass density. For resonantly produced $X_{17}$ the boost factor is rather small $\gamma_{X_{17}} = \frac{M_X}{2m_e} \sim 17$, implying that even for the smallest experimentally allowed couplings, $X_{17}$ decays will occur promptly, with typical decay lengths never exceeding $O(1)$ cm.

The $X_{17}$ particle mass is constrained by nuclear data to lay in the limited range given in Eq. (1), which suggests the range in which the beam energy should be varied in order to optimise the $X_{17}$ search strategy. In this work we will consider a “conservative” strategy in which the beam energy is varied in the interval $E \in [265, 297]$ MeV, which corresponds to a scan in the centre-of-mass (CM) energy range $\sqrt{s} \in [16.46, 17.42]$ MeV, that is a 2σ range around the $X_{17}$ mass hint as measured in $^4\text{He}$. We will also show the projected sensitivity for a more “aggressive” search, in which the beam energy is restricted to vary in the interval $E \in [273, 291]$ MeV, corresponding to $\sqrt{s} \in [16.72, 17.25]$ MeV, that is a 2σ range around the $X_{17}$ mass hint obtained by a naive combination (i.e. neglecting possible correlations) of the $^4\text{He}$ and $^3\text{Be}$ ATOMKI measurements [2, 3].

The sensitivity of the scanning procedure depends on the energy step $\Delta E$ used in the scan. For a Gaussian beam energy distribution the number of produced $X_{17}$ falls exponentially fast when the mean beam energy $E$ departs from the resonance energy $E_{\text{res}}$, and reaches a minimum when $|E - E_{\text{res}}| = \Delta E/2$. Denoting by $\alpha$ the relative variation of the projected limit obtainable with the highest vs. lowest production rates, the energy step $\Delta E$ can be determined in terms of $\alpha$ as

$$\Delta E \approx 4\sigma_E \sqrt{\alpha}.$$

(8)

For the projections of the PADME Run III sensitivity discussed below we require $\alpha \sim 20\%$. Finally, a useful approximation to the production rate of a vector $X_{17}$, that in our setup with a 100μm diamond target holds to a few percent level, is given by

$$N_{X_{17}}^{\text{Vec.}} \approx 1.8 \times 10^{-7} \times \left( \frac{g_{ve}}{2 \times 10^{-4}} \right)^2 \left( \frac{1 \text{ MeV}}{\sigma_E} \right).$$

(9)

where we have assumed that the beam energy is centred on the resonant energy $\sqrt{s} = M_X$. 

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1 This is a very good approximation for all electrons in the 2s, 2p and 1s atomic shells of $^{12}\text{C}$ [34, 43].

2 For positron energies $E_+ \sim 10-20$ MeV the typical energy loss in crossing a 100 μm diamond target is of the order of $O(100)$ keV.

Typical values of the PADME beam spread $\sigma_E$ are of $O(1)$ MeV, so distortion effects on the energy distribution can be neglected.
In the case where the $X_{17}$ is a pseudo-scalar particle (axion-like particle, or ALP in the following), the relevant Lagrangian is
\[
\mathcal{L}^{\text{ALP}} \supset \sum_{f = e, u, d} g_{f} m_{f} X_{17} \bar{f} \gamma^{5} f.
\] (10)

The production cross-section is given by [44]
\[
\sigma_{\text{res}}^{\text{ALP}} = \frac{\pi m_{e} g_{a}^{2}}{4} \times \delta(E_{+} - E_{\text{res}}).
\] (11)

Since photon couplings are independent of the initial and final state fermion chiralities, radiative correction are similar to the case of a vector $X_{17}$. Thus, for the case of a pseudo-scalar $X_{17}$ produced by a positron beam tuned at the resonant energy, and decaying into an electron-positron pair, we have
\[
N_{X_{17}}^{\text{ALP}} \approx 5.8 \cdot 10^{-7} \times \left( \frac{g_{\mu}}{\text{GeV}^{-1}} \right)^{2} \left( \frac{1 \text{ MeV}}{\sigma_{E}} \right).
\] (12)

In case the $X_{17}$ decays also into photons or into other dark sector particles, this result should be multiplied by $\text{BR}(X_{17} \to e^{+}e^{-})$.

### III. THE PADME EXPERIMENT RUN III

The DAΦNE BTF at LNF offers interesting prospects for a $X_{17}$ search based on resonant production [34]. In particular, the LNF accelerator complex can provide a positron beam and vary its energy in the required range around 280 MeV. Assuming a typical diamond target (with electron density of $10^{24} \text{ cm}^{-3}$) of 100 $\mu$m such as the one actually in use in the PADME experiment [41, 42] several thousand of $X_{17}$ can be produced per $10^{10}$ positrons on target (PoT).

For this reason the PADME experiment has planned a dedicated data taking to search for $X_{17}$ exploiting resonant production, called Run III. For this run, starting in the autumn of 2022, the detector has been optimised to measure $X_{17}$ visible decays. Using the ECal instead of the charged particle veto to detect the electron positron pairs will allow PADME to reach a much stronger rejection of the beam related background with respect to Run II conditions. To suppress the photon background a new detector called ETag has been assembled. It is made of 5mm thick bars of plastic scintillators covering the front face of the PADME ECal. Due to the low $Z$ of plastic scintillators and to their very small thickness, the bars will only be sensitive to charged particles, allowing to separate photons from electrons and positrons.

As mentioned above, PADME plans to carry out a scan on various energy bins in order to cover thoroughly the interesting parameter space. Due to the fact that the $X_{17}$ width is much smaller than the beam energy spread $\Gamma_{X} \ll \sigma_{E}$, the $X_{17}$ particle is expected to contribute to the measured $e^{+}e^{-} \to e^{+}e^{-}$ rate in mostly a single bin of the scan, the one in which $|M_{17} - \sqrt{8}|$ is minimum. Since the excess will occur within a single energy point, the remaining ones will directly measure the background, so that the significance of the excess can be directly inferred from the data, without appealing to any MC simulation.

As will be detailed in the next section, according to the predicted signal and background rates, that are summarised in Tab. 1, the excess of electron-positron pairs due to $X_{17}$ production/decay could be at the sub percent level. Quantifying precisely the confidence level of the exclusion limits (or of a detected excess in the signal) will thus require an extremely precise control on the acquired luminosity point by point. Measuring simultaneously, using ECal, the rate for the $e^{+}e^{-} \to e^{+}e^{-}$ and for the $e^{+}e^{-} \to \gamma\gamma$ processes will allow to monitor the variation of their ratio which is not affected by the previous uncertainty. This strategy drastically reduces systematic effects with respect to single measurements of the $e^{+}e^{-} \to e^{+}e^{-}$ rate, since systematic errors related to both, luminosity and acceptance measurements, cancel in the ratio.

We will present the projection for the PADME Run III based on two scenarios for the total number of PoT and beam energy resolution:

- **Conservative**: $2 \cdot 10^{11}$ total PoT on target, a 0.5% beam spread, a broad energy range [265, 297], and an energy scan with 12 bins.
- **Aggressive**: $4 \cdot 10^{11}$ total PoT on target, a 0.25% beam spread, a narrower energy range [273, 291], and an energy scan with 14 bins.

In both cases, the number of steps were optimised based on the averaged projected limits. Note that the reach is only mildly reduced by further increasing the number of steps. Both scanning strategies are illustrated in Fig. 1, where a first estimate of the irreducible background level is also shown. The total number of positron on target per energy point required is of the order of $10^{10}$. Using $\sim 2500$ positron on target per bunch PADME will be able to collected the necessary statistics in a few days of fully efficient running. Reducing the beam spread $\sigma_{E}$ implies that a larger number of energy steps must be used to cover the whole interesting region. For a fixed number of total positrons on target, the larger production rate per positron from Eq. (7) is therefore compensated by the smaller number of positrons available for each energy point. However, as the number of background events is proportional to the number of impinging $e^{+}$, reducing the energy beam spread ultimately increases the signal-to-noise ratio in each energy bin, thus rising the sensitivity to signatures of NP and improving the projected experimental reach.

### IV. MAIN BACKGROUND PROCESSES

The use of resonant production offers a unique opportunity for enhancing the $X_{17}$ productions rates compared
to the associated $e^+e^- \rightarrow \gamma X_{17}$ production. However, it also introduces challenging QED background sources which are hard to constrain. Given that the resonant production of $X_{17}$ requires a low CoM energy of $\sim 17\,\text{MeV}$, the main background sources are:

- **t- and s-channel Bhabha scattering**
- $e^+e^- \rightarrow \gamma\gamma$
- $e^+N \rightarrow e^+N + \gamma$

While Bhabha scattering is producing the same final state as $X_{17}$ decays, the remaining processes produce at least one photon. In detectors using a pure calorimetric approach photons and electrons are indistinguishable, implying that a non negligible background contribution from photons final state can arise. We will first concentrate on Bhabha scattering, assuming that photons background can be controlled by identifying photons in the final state, as will be discussed in the Sec. IV B. We will study the two Bhabha contributions separately to provide a better understanding of the physics at fixed target, neglecting their interference term. The interference term has been checked to be negative and to produce a reduction of the total cross section below the $\%$ level.

### A. The Bhabha scattering background

The unique Standard Model (SM) process that can produce final states identical to the $X_{17}$ decays at CoM energies in the MeV range is $e^+e^- \rightarrow \gamma^* \rightarrow e^+e^-$, where $\gamma^*$ denotes an off-shell photon. In the SM, Bhabha scattering proceeds via two different contributions, namely the $t$-channel and $s$-channel amplitudes depicted in Fig. 2. While the final state is the same, their kinematic, especially in in fixed target experiments, is very different. The $t$-channel process, despite being dominant in terms of contributions to the total cross section, can be efficiently rejected having a quasi elastic behaviour, with the positron retaining almost all of its original energy, and the electron remaining almost at rest (green distribution in Fig. 3). This is a characteristic of the fixed target experiments in which the initial energy of the two particles is very different. Even exploiting the different kinematics the contribution of $t$-channel process cannot be neglected. The $s$-channel process on the other hand has the same kinematics of the signal $e^+e^- \rightarrow X_{17} \rightarrow e^+e^-$ because the virtuality of the off-shell photon is $\sqrt{s} \sim M_X$. For this reason the $s$-channel process constitutes an irreducible source of background, and represents the limiting factor for the sensitivity of experiments that exploit resonant production.

### B. Photon background

In order to control the photon related background a detector separating electron from photon clusters is required. For this reason during Run III a new detector
| BG Process       | # of Ev | # of Ev. in Acc. | Acc. |
|------------------|--------|-----------------|------|
| $e^+e^- \rightarrow e^+e^-$ (t-ch.) | $5.4 \times 10^7$ | $6.9 \times 10^4$ | 0.13% |
| $e^+e^- \rightarrow e^+e^-$ (s-ch.) | $3.2 \times 10^4$ | $6.4 \times 10^3$ | 20%  |
| $e^+e^- \rightarrow \gamma\gamma$ | $2.9 \times 10^5$ | $1.3 \times 10^4$ | 4.5%  |
| $e^+e^- \rightarrow X_{17} \rightarrow e^+e^-$ | 1250 | 250 | 20% |

TABLE I. Expected number of background and signal events per $1 \times 10^{10}$ positrons on target. The $t$–channel values before selection cuts correspond to $e^\pm$ with energies larger than 1 MeV. The acceptance cuts do not include the $\gamma\gamma$ tagging from the ETag.

called ETag will be introduced in the original PADME setup. ETag will produce signals only if the crossing particle is electrically charged, with a few percent mis-tagging probability of identifying a photon as a charged particle.

The two photon annihilation process is the most relevant photon based source of background due to the large cross section and reduced effectiveness of the kinematical constraints. Assuming a mis-tagging probability $\epsilon_{mis} = 5\%$ a rejection factor on the $e^+e^- \rightarrow \gamma\gamma$ process of $1/\epsilon_{mis} = 400$ can be obtained. Such a value, if achievable, would reduce the background originating from two photon annihilation to a negligible level.

Positron bremsstrahlung can also originate events with two charged particles, if the radiated photon is mis-tagged as a charged particle, and the two particles are entering the ECal acceptance. Both these conditions are rare, being the process dominated by high energy forward positrons and soft forward photons crossing the PADME ECal central hole. In addition, the two cluster eventually produced in the ECal will hardly reproduce the correct invariant mass value of 17 MeV. For this reasons the background coming from bremsstrahlung can be considered as negligible.

C. Beam related and pile up backgrounds

An additional possible source of background comes from overlapping beam-target interactions or beam related background. In the first case interactions of two different primary positrons can produce two simultaneous clusters in the PADME ECal. In the second case the interactions of the beam halo with beam line elements can produce multiple clusters events. These sources of background are proportional to the beam intensity which will be reduced to few thousand $e^+/\text{bunch}$ in PADME Run III, a factor 10 lower with respect to PADME Run II.

Combinatorial backgrounds sources can be controlled by applying several kinematical constraints to the event selection. The Bhabha kinematics is highly constrained so that the energy and the polar angle of each of the leptons are connected by an analytic expression, $E_{e^\pm} = f(\theta_{e^\pm})$. A simple set of conditions can be applied to reject combinatorial backgrounds:

- $E_{e^+} + E_{e^-} = E_{\text{beam}}$
- $M^2(e^+e^-) = \sqrt{s}$
- $E_{e^\pm} = f(\theta_{e^\pm})$

This strategy is well understood, and has been proven to be quite effective in the analysis of $e^+e^- \rightarrow \gamma\gamma$ events during PADME Run II [45].

D. Expected backgrounds summary

Let us now summarise the expected background contribution obtained by simulating final state kinematics with the CalcHEP package. We compute the total number of expected events using the cross section provided by CalcHEP, and we evaluate the acceptance adopting the following strategy:

- The energy of both outgoing particles $E_1, E_2$ is in the range: $E_{1,2} > 100$ MeV.
- The azimuthal angle of both particles $\theta_1, \theta_2$ is in the range: $25.5 \lesssim \theta_{1,2}/\text{mrad} \lesssim 77$.

Applying these conditions we find the number of signal and background events for each energy point of the scan ($\sim 1 \times 10^{10}$ poT). Our results are summarised in Tab. I. The signal rate has been obtained for $g_{ee} = 2 \cdot 10^{-4}$ which saturates the unexplored region of parameter space for vector particles. For the above background level, projected limits at 90% C.L. will thus correspond to having less than $\sim 360$ NP events [3]. Tab. I shows that the $X_{17}$ production rate is non negligible with respect to the background even for small values of the $g_{ee}$ coupling. The resulting signal acceptance has been obtained using Bhabha s-channel kinematics, which is expected to be identical to the $X_{17}$ one for prompt $X_{17}$ decays. The actual acceptance value will depend on the final experimental cut strategy.

V. PROJECTIONS

In Fig 4 we show the projections of the constraints on $g_{ee}$ for the case of vector $X_{17}$ as function of its mass. For a vector particle with mass $M_X \approx 17$ MeV the parameter space below $g_{ee} = 0.2 \cdot 10^{-3}$ is excluded by a combination of E141 [17] and NA64 experiments [23] as well as by other beam dump experiments [21, 22]. As can be seen from the picture, in the vector boson case the projected sensitivity of PADME Run-III reaches down all the way to the upper limit from NA64, completely covering the still viable parameter space region. PADME

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3 We assume that the $\gamma\gamma$ background will be reduced to a negligible level from the tagging in the ETag detector.
Run-III will thus exhaustively probe the hypothesis that the ATOMKI anomaly is due to a new vector boson with mass $M_X \approx 17$ MeV.

In the case the $X_{17}$ is instead a spin-0 ALP, the existing limits are significantly less constraining due to the somewhat shorter lifetime and the slightly reduced production rate of an $X_{17}$ ALP compared to a vector boson. In particular, we see from Fig. 5 that the NA64 limit [23] is barely reaching into the parameter space region favoured by the nuclear experimental data. In contrast, the projections corresponding to the regions in orange indicate that PADME Run-III will be able to probe a significant part of the viable parameter space for an $X_{17}$ ALP.

VI. CONCLUSION

In this work we have described a novel approach to probe the existence of the putative $X_{17}$ boson hinted by the anomalies in $^8$Be and $^4$He nuclear transitions reported by the ATOMKI collaboration, and more generally of any new light boson with a mass close to 17 MeV and coupled to $e^\pm$. By exploiting the resonant annihilation of positrons of an energy-tuned beam on atomic electrons in a thin target, the scan-based procedure that we have described can be used to extract the signal, while fitting the background directly from the off-resonance data.

We have studied the implementation of this strategy in the upcoming Run-III of the PADME experiment at LNF. We have worked out a number of projections based on a statistic of a few $\times 10^{11}$ total number of positrons on target. We have considered only statistical errors on signal and background. However, there are good reasons to expect that systematic errors could be kept to a similar level, including in particular the uncertainty on the relative number of positrons on target collected at each energy point of the scan. In this case several weeks of data-taking at PADME would be sufficient to cover completely the parameter space region still viable for a spin-1 $X_{17}$ candidate. In contrast, it will not be possible to completely exclude (or discover with certainty) a spin-0 $X_{17}$ ALP, but still it will be possible to reduce significantly the viable parameter space. It is worth mentioning at this point that, since the remaining parameter space for an $X_{17}$ ALP lays in the small coupling region, typical decay lengths can be as large as $\sim 1$ cm. Hence, if a sufficiently precise vertexing of the decay could be engineered, the background would be dramatically reduced, and eventually it might be possible to close also this region.

While this work has focused on the mass range $M_X \in [16, 18]$ MeV as determined by the BTF beam energy range, the same technique could be used in the future to probe all types of light bosons feebly interacting with $e^\pm$ with masses in the tens of MeV range, based on the availability of positron beams of adequate and tunable energies.

Note added

Shortly after the completion of this paper an arXiv preprint of the ATOMKI collaboration appeared [46] that reports the observation of a further anomaly in the large angles correlation of $e^+e^-$ pairs produced in $^{12}$C nuclear target.
transitions. This new anomaly is consistent with the $X_{17}$ vector boson interpretation of the $^8\text{Be}$ and $^4\text{He}$ anomalies, but it is at odd with a $X_{17}$ of pseudoscalar nature [5].

Acknowledgements

We acknowledge several discussions with members of the PADME collaboration and in particular P. Valente for fundamental inputs on the LNF beam setup, and P. Gianotti for discussions on the details of the PADME experimental strategy. L.D. and E.N. have been supported in part by the INFN “Iniziativa Specifica” Theoretical Astrophysics Physics (TAsP-LNF). E.N. and M.R. are partially supported by the Sapienza Grant “Ricerca del bosone X17 nell’esperimento PADME ai laboratori Nazionali di Frascati.”. L.D. is supported by the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 101028626 from 01.09.2021. M.M. acknowledges professor A. D’Angelo for bringing him in contact with Beyond Standard Model Physics.

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