Frascati Physics Series Vol. 67 (2018)
6th Young Researcher Workshop 'Physics Challenges in the LHC Era'
May 7 and 10, 2018

DARK-PHOTON PRODUCTION IN e^+ BEAM-DUMP EXPERIMENTS VIA RESONANT e^+e^- ANNIHILATION

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Abstract

We explore the foreseeable sensitivity of the Frascati PADME experiment to searching, with the resonance annihilation technique, for the 17 MeV dark photon invoked to explain the ^{8}Be anomaly in nuclear transitions. This involves a positron beam-dump experiment where, due to the continue loss of energy from soft photon bremsstrahlung in the first few radiation lengths of the dump, the positron beam can continuously scan for resonant production of new resonances via e^+ annihilation off an atomic e^- in the target.

1 Introduction

Neutrino masses, the cosmological baryon asymmetry and dark matter (DM) are some experimental facts that remain unexplained within the fundamental physics framework known as the standard model (SM) of particle physics and call for physics beyond it. This might correspond to a whole new sector containing new particles, as well as new interactions. If such a sector exists, one possible reason why it has not been discovered yet is that the couplings between the new particles and the SM are so feeble that the whole new sector has so far remained hidden, even if the mass scale of the new particles, including the mediators of the new forces, is within the experimental reach. This scenario has triggered in recent years an increasing interest in many novel ideas to hunt for new physics at the intensity frontier. In particular, the so-called dark photon (DP) A', a massive gauge boson arising from a new $U(1)'$ gauge symmetry, can be considered as a natural candidate for a superweakly coupled new state because the dominant interaction with the SM sector might arise solely from a mixed kinetic term $(\epsilon/2)F'_{\mu\nu}F^{\mu\nu}$. The coupling ϵ between the $U(1)'$ and QED field strength tensors has values naturally falling in a range well below 10^{-2}, and constrained by different experimental considerations [1].

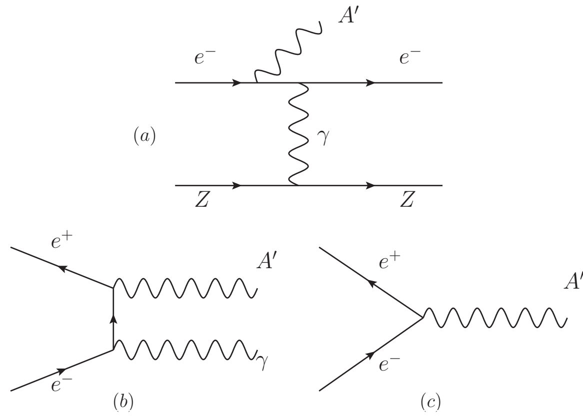

Figure 1: A' production modes in fixed target electron/positron beam experiments: (a) A-strahlung in e^--nucleon scattering; (b) A'-strahlung in e^+e^- annihilation; (c) resonant A' production in e^+e^- annihilation. Figure adapted from [4].

From the phenomenological point of view, light weakly-coupled new particles have been invoked to account for discrepancies between SM predictions and experimental results, such as, for example, the anomaly observed by the Atomki collaboration in the decay of excited ^{8}Be nuclei to the ground state [2]. This anomaly can be interpreted as due to the emission of a new boson with mass 17 MeV, i.e. the DP, in the decay $^8\text{Be}^* \to\ ^8\text{Be} + A'$ followed by $A' \to e^+e^-$. This anomaly is particularly relevant since the new experimental technique that we are going to describe appears to be well suited to test (at least in some region of the parameter space) the particle physics explanation based on a new gauge boson with mass $m_{A'} \sim 17\,\text{MeV}$, kinetically mixed with the photon [3].

2 Framework

2.1 The Beryllium Anomaly and DP constraints

The beryllium anomaly consists in the observation of a bump in the opening-angle and invariant-mass distributions of electron-positron pairs produced in the decays of excited ^{8}Be nucleus, which seems unaccountable by known physics. The anomaly has a statistical significance of 6.8σ which excludes the possibility that it arises as a statistical fluctuation. The shape of the excess is remarkably consistent with that expected if a new particle with mass $m_{A'} = 17.0 \pm 0.2(\text{stat}) \pm 0.5(\text{sys})\,\text{MeV}$ is produced in these decays [2, 3]. In the Atomki setup, these decays must occur at a few-cm distance between the target, where the ^{8}Be excited state is formed, and the detectors. This implies a lower limit in the strength of the A' coupling to e^+e^- pairs given by $\epsilon \gtrsim 1.3 \times 10^{-5}$. Stronger limits than those imposed by the Atomki experimental setup are obtained from electron beam dump experiments and are showed in Fig. 3. From these limits we obtain $7 \times 10^{-5} \le \epsilon \le 1.4 \times 10^{-3}$ as the window allowed for a 17 MeV A' decaying dominantly into e^+e^- (visible decay) [4].

2.2 Beam dump experiments

Collider searches for DP have been carried out in fixed target experiments, which can be divided as:

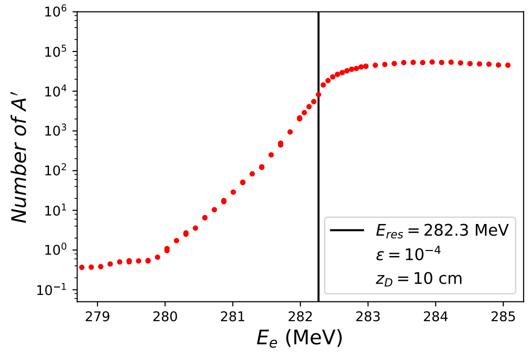

Figure 2: The number of DP decaying outside the dump as a function of the beam energy for $\epsilon = 10^{-4}$ and $z_D = 10\,\text{cm}$. The vertical line corresponds to the energy for resonant production of a 17 MeV DP [4].

1. Electron beam-dump experiments assuming A'-strahalung as the leading production mechanism in electron-nucleon scattering. Parametrically, this process is of order α^3 [5].
2. Positron beams where the production mechanism considered so far is analogous to the usual QED process of positron annihilation off an atomic target electron with two final state photons, where one photon is replaced by one A'. This corresponds to a process of $\mathcal{O}(\alpha^2)$ [6][1];
3. Resonant e^+e^- annihilation into on-shell A' which, being of $\mathcal{O}(\alpha)$, is parametrically enhanced with respect to the previous two production channels [4]. Besides experiments with positron beams, resonant annihilation must also be accounted for a correct analysis of electron beam dump experiments, since positrons are abundantly produced in the electromagnetic shower inside the dump [7];

These production mechanisms are depicted in Fig. 1(a-c), respectively. The last two are specific production processes considered in the PADME experiment at the DAΦNE LINAC Beam Test Facility (BTF) of the INFN Laboratori Nazionali di Frascati (LNF). This experiment is designed to search for DP by using a positron beam impinging on a thin (thick) target of low (high) atomic number. The experiment will use a 550 MeV positron beam impinging on a 100μm thin active target made of polycrystalline diamond ($Z = 6$) for the process 2 (Fig. 1(b)) and a tungsten target ($Z = 74$) of several cm of length (z_D =2, 5 and 10 cm) for the process 3 (Fig. 1(c)) [4].

2.2.1 Resonant e^+e^- annihilation

This new proposal to search for DP has several advantages that suggest that it might be particularly convenient to operate the PADME (as well as others) positron beam fixed target experiment in a dedicated mode in order to search for A' via resonant production. One of the advantages is due to the use of the thick target. In this case, it is possible to absorb most of the incoming positron beam, as well as the related electromagnetic showers, and in any case to degrade sufficiently the energy of the residual emerging particles, so that the background from charged particles can be easily deflected and disposed of. Also, the

[1]The A' can be detected in the invisible channel by searching for a narrow bump in the spectrum of the missing mass measured in single photon final states, originated via $e^+e^- \to \gamma A'$.

DP produced in e^+e^- annihilation, if sufficiently long-lived, will escape the dump without interacting and will decay inside the downstream vacuum vessel, producing an e^+e^- pair of well-defined energy. A second advantage is that using the thick target can provide an almost continuous energy loss for the incoming positrons propagating through the dump so that they can efficiently "scan" in energy for locating very narrow resonances [4]. In this scheme, we will estimate the sensitivity to the A' couplings that could be achieved with targets with $z_D = 2$, 5 and 10 cm in the PADME experiment. The number of detectable DP events is then given by (see reference [4] for more details):

$$N_{A'} = \frac{N_{e^+} N_0 X_0}{A} e^{-\frac{z_D}{\ell_\epsilon}} \int_0^{T=1} dt\, e^{\frac{X_0}{\rho \ell_\epsilon} t} \int_0^\infty dE_e \left[\int_0^\infty \mathcal{G}(E)\; I(E, E_e, t)\; dE \right] \sigma_{\rm res}(E_e) \,, \tag{1}$$

where $\mathcal{G}(E) = \mathcal{G}(E; E_b, \sigma_b)$ is a Gaussian that describes the energy distribution of positrons inside the BTF beam, with $250 \leq E_b/\text{MeV} \leq 550$ the nominal energy and $\sigma_b/E_b \sim 1\%$ the energy spread. $I(E, E_e, t) = \theta(E - E_e)[\log(E/E_e)]^{\frac{4}{3}t-1}/[E\,\Gamma(4t/3)]$ is the probability that a positron with initial energy E will have an energy E_e after traversing $t = \rho z/X_0$ radiation lengths (with ρ being the density of the material in g/cm^{-3} and $X_0 = 6.76\,\text{g/cm}^{-2}$ the unit radiation length in tungsten). $\ell_\epsilon \sim 3/(2m_e\alpha\epsilon^2)$ is the decay length of the DP, N_{e^+} the number of incident positrons, N_0 the Avogadro number, $A = 184$ the atomic mass of tungsten, and $\sigma_{\rm res}$ the resonant cross section given by (using the narrow width approximation):

$$\sigma_{\rm res}(E_e) = \sigma_{\rm peak} \frac{\Gamma_{A'}^2/4}{(\sqrt{s} - m_{A'})^2 + \Gamma_{A'}^2/4} \,, \tag{2}$$

where $s \simeq 2m_e E_e$, $\sigma_{\rm peak} \simeq 12\pi/m_{A'}^2$ and $\Gamma_{A'} \simeq \epsilon^2 \alpha m_{A'}/3$.

Taking into account Eq. (1) and assuming that the background remains constant when the beam energy is varied by a few MeV (as a consequence of the "scan" in energy), the background can be directly measured from the data and gives an estimate of the number of events created in the resonance annihilation mode. This is illustrated in Fig. 2 where we can see that when the beam energy is increased towards the resonance value (given by the vertical line) the number of produced e^+e^- pairs increases in a step-wise way up to a maximum, and then remains approximately constant with increasing energy, due to positron energy losses in the material, which drive their energy towards $E_{\rm res}$.

Effects of target e^- velocities

Inside materials, the electrons are not at rest and, in the case of large atomic numbers, like tungsten, can have large velocities. For positron annihilation in this type of materials, the center-of-mass energy can differ sizeably from what can be naively estimated in terms of the beam energy, energy spread, energy loss due to in-matter propagation, and assuming electrons at rest. Then, to take into account this fact, we consider the positron-annihilation probability distribution as a function of the electron momentum[2], $\mathcal{P}(v_e) = \left[1.015^{-v_e^2} + 1.112^{-2v_e} + \theta(v_e - 40)\, 3 \times 10^{-6+\frac{1}{v_e}}\right]/12$, replacing the Mandelstam variable s in Eq. (2) by [4]:

$$s(v_e, \chi) = 2m_e \left\{ E_e \left[1 - \mathcal{P}(v_e) v_e \, \frac{1}{2} s_\chi c_\chi \right] + m_e \right\} \,, \tag{3}$$

[2] Since annihilation with delocalized and weakly bound valence electrons, which contribute to the low-momentum part of the momentum distribution, is more likely than annihilation with the localized and tightly bound core electrons contributing to the high-momentum part (for more details see discussion about Fig. 3 in reference [4]).

$\epsilon \big/ N_{A'}^{\text{prod}}$	E_{res} $(v_e = 0)$	E_{res}	$E_{\text{res}} + 2\sigma_b$
1.0×10^{-3}	7.69×10^{11}	1.51×10^{11}	4.72×10^{11}
5.0×10^{-4}	1.81×10^{11}	3.79×10^{10}	1.17×10^{11}
1.0×10^{-4}	7.25×10^{9}	1.49×10^{9}	4.73×10^{9}

Table 1: Number of 17 MeV DP produced in the first radiation length of a tungsten target for three different values of ϵ. The second and third columns are for a beam energy tuned to the resonant value $E_{\text{res}} = 282.3\,\text{MeV}$, assuming the electron at rest and with the velocity distribution $\mathcal{P}(v_e)$, respectively. The last column, also including v_e effects, is for a beam energy $E_b = E_{\text{res}} + 2\sigma_b$ [4].

where $c_\chi = \cos\chi$ accounts for the projection of $\vec{v}_e$ along the z-direction of the incoming positron and $s_\chi/2$ with $s_\chi = \sin\chi$ is the probability distribution for the angle χ. The cross section is also integrated over c_χ and $v_e \in [0, 0.06]$.

3 Results

Table 1 shows some results that illustrate how the number of DPs within the first radiation length of tungsten are modified when is considering v_e inside the target for different values of the parameter ϵ. The second column gives the results for a beam energy tuned at the resonant energy $E_{\text{res}} = 282.3\,\text{MeV}$, when the motion of the target electrons is neglected. Meanwhile, the third column gives the results obtained when the electron velocity is taken into account. From this table we can see that the shift due to the electron momentum has the effect of reducing the number of DPs produced by about a factor of five. The last column gives the results for a beam energy tuned above the resonance $E_b = E_{\text{res}} + 2\sigma_b$. In this case, the number of DP is increased by about a factor of three regarding the number of DPs generated just at resonance. This is because of the "scan" in the positron energy inside the target.

In Fig. 3 the black hatched region depicts the forecasted sensitivity of PADME in thin target mode, which will search for DP via the $e^+e^- \to A'\gamma$ process. The light cyan trapezoidal regions represent the constraints that PADME could set by running in thick target mode, and are respectively for tungsten targets of 10 cm, 5 cm and 2 cm of length assuming zero background. The width of these regions spans the interval $16 \lesssim m_{A'}/\text{MeV} \lesssim 23.7$ which corresponds to the Frascati BTF energy range for positron beams $250 \lesssim E_b/\text{MeV} \lesssim 550$.

4 Conclusions

A new way to search for DPs, coupled to e^+e^- pairs, via resonant production in e^+e^- annihilation is suggested as an alternative method to test new physics at high intensity accelerators. This production mode together with the A'–strahlung in e^+e^- annihilation, are two complementary modes in the PADME experiment, since they can set new bounds in the regions of small $\mathcal{O}(10^{-4})$ and large $\mathcal{O}(10^{-3})$ values of the DP mixing parameter ϵ, respectively. With some intense and dedicated experimental efforts, the black-hatched region and the trapezoidal-shaped areas shown in Fig. 3 could be explored by the PADME experiment. In particular, the allowed window to produce, via resonant e^+e^- annihilation, the 17 MeV DP can be invoked to explain the ^{8}Be anomaly. A confirmation of the DP interpretation of the ^{8}Be anomaly (studying the inverse process $e^+e^+ \to A'$ at accelerators) at the intensity frontier, would possibly represent the discovery of a hidden sector and a particle physics breakthrough. The resonant $e^+e^- \to A'$ production can be relevant also in the case of electron beam dump experiments, since secondary positrons

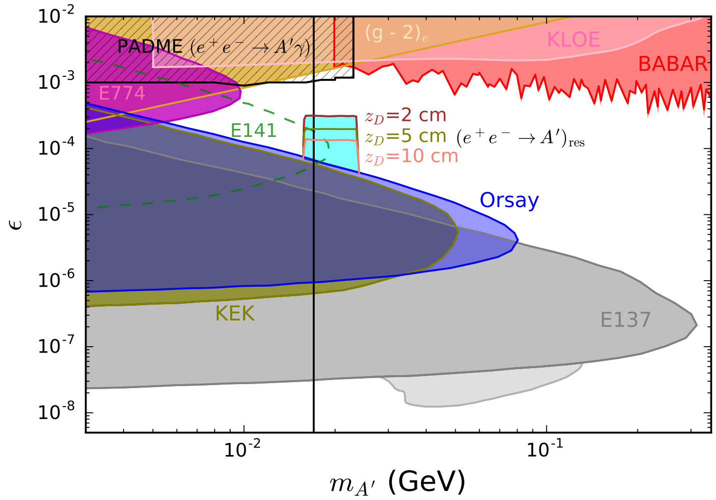

Figure 3: Limits on the DP kinetic mixing ϵ as a function of the mass $m_{A'}$ from different experiments. The region that could be excluded by PADME running in thin-target mode is hatched in black, while the three trapezoidal-shaped areas give the PADME reach in thick-target mode, respectively for a 10, 5 and 2 cm tungsten dump, assuming zero background [4].

that could trigger the annihilation process are abundantly produced in electromagnetic showers. This observation was recently exploited in a reanalysis of the SLAC E137 data which extend the previously excluded region towards smaller ϵ values, as is shown by the light gray area in Fig. 3 [7].

5 Acknowledgements

The author acknowledges COLCIENCIAS in Colombia (doctoral scholarship 727-2015) for financial support and the LNF Theory Group for hospitality and partial financial support to attend the XIX LNF Spring School “Bruno Touschek” in Nuclear, Subnuclear and Astroparticle Physics.

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