Status of the PADME experiment

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Abstract. Among the theoretical models addressing the dark matter problem, the category based on a secluded sector is attracting increasing interest. The PADME experiment, at the Laboratori Nazionali di Frascati of INFN, is designed to be sensitive to the production of a low mass gauge boson $A'$ of a new U(1) symmetry holding for dark sector particles and weakly coupled to the Standard Model photon. The DAΦNE Beam-Test Facility at LNF will provide a high intensity, mono-energetic positron beam impinging on a low Z target. The PADME detector will measure with high precision the momentum of the photon, produced along with the $A'$ boson in $e^+e^- \rightarrow A'\gamma$ annihilation in the target, thus allowing to measure the $A'$ mass as the missing mass in the final state. This technique, particularly useful in case of invisible decays of the $A'$ boson, will be exploited for the first time in a fixed target experiment. Simulation studies predict a sensitivity on the interaction strength ($\epsilon^2$ parameter) down to $10^{-6}$, in the mass region $1 \text{ MeV} < M_{A'} < 23.7 \text{ MeV}$. In this work the physics potential, the experimental strategy and the status of readiness of the experiment will be reviewed.

1. Introduction

Several compelling astrophysical observations lead to the conclusion that the dominant content of the energy-matter density of the Universe is energy, in an unknown form, while matter contribute to 31%, out of which 26% is non-barionic dark matter. Observations constrain this new form of matter to be cold, stable and weakly interacting with Standard Model (SM) particles. Among the dark matter particle candidates the theoretically most appealing option has been the lightest supersymmetric particle of a R-parity conserving SUSY model. Nowadays, the searches for SUSY at LHC have shrunk a lot the parameter space of a natural SUSY and the interest for new physics scenarios with a secluded sector has considerably grown. The idea behind this paradigm is that dark matter is effectively hidden since it is not connected by gauge symmetries to the SM. A tiny connection between ordinary matter particles and the dark matter particles is established only via “portals”. Several implementations of this idea have been suggested; they are referred as the

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Figure 1. Existing constraints on the dark-photon parameter plane, $\epsilon$ (or $\epsilon^2$) and $m_{A'}$, derived in the search for visible (left) and invisible (right) decays of the $A'$ boson. The plots are extracted from Ref. [2] and [3].

**Higgs portal**, when the connection is established through the scalar sector of an unconventional Higgs boson, or the **Vector portal**, when a spin one gauge boson of the hidden sector allows the communication between SM and dark matter. In the simplest possible model, a $U_d(1)$ gauge symmetry holds in the dark sector and the corresponding vector boson, the “dark photon” $A'$, acts as a vector portal through an effective coupling to the SM photon. This effective coupling is described by a parameter $\epsilon$ that multiplies the electric charge of the SM fermion. In principle, $\epsilon$ can be a flavor dependent parameter or it can be a universal constant, like in the hypothesis that it dominantly originates from the dynamic-mixing of the two $U(1)$ gauge groups coexisting in the Lagrangian. The model is predictive and easy to test as a function of only two parameters: $\epsilon$ and $m_{A'}$, the mass of the gauge boson, which might be generated through some symmetry breaking mechanism. A comprehensive review of the motivations and phenomenological implications of the model is given in [1] and [2] along with a summary of constraints from past and planned experiments. The dark photon search strategy depends heavily on the hypotheses of possible decays into invisible dark matter pairs, with branching ratio close to unity, or exclusive decays into SM fermion pairs ($e^+e^-$, $\mu^+\mu^-$, etc). Due to the clean signature of the visible decays, stringent constraints exist thanks to various dedicated experiments and re-interpretation of past results (see Figure 1-left$^2$); much less experimental activity has explored the $\epsilon^2$, $m_{A'}$ plane under the hypothesis of dominant invisible decays of $A'$. The most stringent constraints, produced by the BaBar [3] and the NA64 [4] experiments are superimposed to indirect limits in Figure 1-right.

2. **PADME design and physics potential**

The PADME experiment [5] at the Laboratori Nazionali di Frascati of INFN is designed to search primarily for invisible decays of the dark photon produced in the process $e^+e^- \rightarrow A' + \gamma$. It exploits a pulsed positron beam produced by the Beam Test Facility (BTF) [6] of the DAΦNE accelerator complex impinging on a thin diamond target. The BTF can provide electron or positron beams of a maximum energy of 750 and 550 MeV respectively. At the beam energy of 550 MeV, $A'$ production can occur for $m_{A'} < 23.7$ MeV. The beam energy spread is below 1%, the beam spot size on the target of about 1 mm with divergence below 1.5 mrad. The pulse current is of about 5000 particles/40 ns, and pulses can be as long as 200 ns, while the main limiting factor is the repetition rate of 50 Hz of the Linac. From a precise measurement of the photon energy

$^2$ All figures in this paper are coloured online.
Figure 2. A schematic view of the PADME detector. A photon and a low energy positron from a typical bremsstrahlung event are superimposed to the sketch for illustration purposes.

and deflection with respect to the incoming beam line, the mass of the undetected $A'$ boson can be measured from the closed kinematics of the signal event: $m_{A'}^2 = (p_{\text{beam}} + p_{e^-} - p_{\gamma})^2$. Therefore the main detector of the PADME experiment is a high resolution electromagnetic calorimeter (ECAL) of cylindrical shape with a central hole, located 3 m downstream of the target on the beam line. A dipole magnet sitting immediately behind the target sweeps the positrons of the beam that didn’t undergo relevant interactions in the target out of the ECAL acceptance. Veto detectors for charged particles are used to instrument the vertical inner sides of the dipole magnet and the region between the dipole and the beam dump; they must ensure that no other particle is produced in time with the photon and they are meant to fight the main background coming from bremsstrahlung interactions in the target ($e^+ + N \rightarrow e^+ + \gamma + N$). Finally, a Small Angle fast Calorimeter (SAC) sitting behind the hole of ECAL measures the total energy of photons emitted in the forward direction. A schematic view of the experiment is represented in Figure 2.

The detection of a peak in the distribution of the squared missing mass measured in events with a single photon and no other activity allows to determine at the same time the mass of the $A'$ boson and the coupling parameter $\epsilon$. This experimental approach, called missing mass technique, has the advantage of being intrinsically independent of the coupling of $A'$ to the dark matter particles it decays to, and of their masses. The annihilation cross section $\sigma(e^+ e^- \rightarrow A' + \gamma)$ is equal to the SM cross section for $e^+ e^- \rightarrow \gamma\gamma$ scaled by a factor of $\epsilon^2 \delta(m_{A'}, E_{\text{beam}})$. The kinematic factor $\delta(m_{A'}, E_{\text{beam}})$ has the constant value of 2 except in the region near the threshold for $A'$ production, when the cross section is enhanced as much as $m_{A'}$ approaches the maximum kinematically allowed value for $A'$ production by a positron beam of energy $E_{\text{beam}}$. For a beam of $E_{\text{beam}} = 550$ MeV, the cross section for the production of a 10 MeV $A'$ is equal to about 3.6 nb if $\epsilon^2 = 10^{-6}$. The most abundant SM process occurring at PADME is bremsstrahlung. It can be suppressed by looking for hits in the positron veto in time, within about 2 ns, with the photon cluster reconstructed in ECAL with energy $E_{\gamma}$. In addition, the sum of $E_{\gamma}$ and of the positron energy $E_{e^+}$, measured from the bending in the magnetic field, must be compatible within experimental resolution with $E_{\text{beam}}$. Other background processes are $e^+ e^- \rightarrow \gamma\gamma$ and $e^+ e^- \rightarrow \gamma\gamma\gamma$. While the latter is suppressed by a factor $\alpha_{\text{em}}$, it can be more insidious due to the asymmetric configuration of the photons in the final state which mimic the single photon topology of the signal events. The measurement of the energy in the SAC can help to recognise $3\gamma$ events where two of the photons escape ECAL through the central hole. For a total number of $10^{13}$ positrons on target, simulation studies show that, under the assumption of a good time resolution of the PADME detectors, rather simple selection criteria can be applied to define a sample of single photon events with good signal efficiency ($\sim 10\%$) and high background rejection that can lead to exclude values of $\epsilon$ larger than about $10^{-3}$ for $m_{A'} < 23.7$ MeV in the absence of excess of events with respect to the SM expectation.

Along with the search for invisible decays of the dark photon, PADME will be able to
investigate other new physics scenarios. Axion-like particles (ALPs) are a theoretical hypothesis that has already been widely scrutinised experimentally. However, in the mass range $0.1 \div 1$ GeV the couplings to electrons and photons are still subject to relatively loose constraints, leaving open the possibility of significant effects as discussed in [7]. At PADME ALPs might be produced in $e^+e^-$ annihilation, through the Primakoff effect, or via bremsstrahlung. Depending on the production mode and on the relative strength of the coupling to electrons and photons, several detectable final states, consisting of missing energy +1$\gamma$ or +1$e^\pm$, if the ALP decays to invisible particles, or of 3$\gamma$, can be in the reach of the PADME detector.

Recently, the long standing claim for an anomaly in the decay of an exited state of $^8$Be received further experimental confirmation [8]. A vector boson with suppressed coupling to the proton or a boson with axial coupling to quarks of mass $\sim 17$ MeV might explain the anomaly while being compatible with existing constraints from the NA48 experiment based on $\pi^0 \rightarrow \gamma e^+e^-$. Such exotic particle $X$ might be produced and detected with PADME in the process $e^+e^- \rightarrow X(e^+e^-)\gamma$, however the sensitivity would be tiny. A recent study [9] suggests to search for the resonant production of $X$ in a setup like PADME with an $e^+$ beam of 282.7 MeV. Several uncertainties may impact the possibility to observe the production of the narrow resonance (electron velocity distribution in the atoms is an example), however, this proposal is potentially an interesting opportunity for PADME.

3. Status of the PADME detector

The PADME target is a $20 \times 20 \times 0.1$ mm$^3$ slab of polycrystalline synthetic diamond, produced by Chemical Vapour Deposition at Applied Diamond Inc. (USA). The low Z of the material is dictated by the need of minimizing the ratio between the rate of bremsstrahlung interactions and signal interactions. On both surfaces 16 strips in orthogonal directions allow to polarize the device and to read the charge profile of the beam in two views at each beam pulse. A continuous recording of the beam centroid and intensity are obtained [10] which are beneficial for the missing mass resolution, through the $\gamma$ direction, and for the measurement of the total flux of positrons impinging on the target during the run. Figure 3(a) shows the diamond target mounted on the PCB holding the pre-amplification electronics (AMADEUS chip). The active target assembly is being integrated at LNF in the vacuum system at the interface of the BTF beam line and the vacuum vessel enclosing the veto detectors and the volume in front of ECAL where interactions of final state particles with the atmosphere must be minimized.

The central detector of PADME is a uniform cylindrical electromagnetic calorimeter of radius 280 mm, with a inner hole of 100 mm diameter consisting of 616 BGO crystals of size $21 \times 21 \times 230$ mm$^3$, coupled to 19 mm diameter photomultipliers XP1911 from HZC Photonics each connected via an optical fibre to waveform digitizers sampling the signal at 1 or 5 GS/s. Beam test results from a prototype show that an energy resolution of $2%/\sqrt{E(\text{GeV})}$ can be achieved [11], fulfilling the design requirement. Special care has been devoted to the design of the overall mechanical assembly, in order to ensure hermeticity, crystal insulation and to minimize losses by passive materials. Figure 3(b) shows a view of the back side of ECAL during the assembly operations. The SAC is a squared matrix of 25 Cherenkov counters $30 \times 30 \times 140$ mm$^3$ made of PbF$_2$ in order to achieve a high rate capability with a dead time below $\sim 3$ ns. Light collection is performed with fast photomultipliers R13748 by Hamamatsu. A time resolution below 90 ns has been measured in beam test data.

The basic unit of the PADME veto detectors is a $10 \times 10 \times 180$ mm$^3$ bar of plastic scintillator, equipped with an optical fiber and readout by a SiPM (Hamamatsu S12572). They are assembled in three arrays of 96, 96 and 16 scintillators, representing two identical detectors for low energy positrons and electrons (shown in Figure 3(c) ready to be mounted on the left and right edges of the dipole magnet, with the scintillator fingers parallel to the magnetic field) and one detector for bremsstrahlung positrons of energy close to the beam energy. Time resolution of about
Figure 3. The CVD diamond active target with the electrical connection via wire bonding of the Y-view graphitic strips to the metallic contacts on the board (a). The construction of the PADME electromagnetic calorimeter (b). Two arrays of 96 scintillating bars assembled and ready to be installed in the experiment as positron and electron veto detectors (c).

500 ps and inefficiency below $\sim 0.1\%$ have been measured in beam test with prototypes [12]. Auxiliary high resolution monolithic pixel detectors are foreseen to help with beam and background diagnostic at the target and in the proximity of the beam dump. Some details about them can be found in [13] and references therein.

4. Conclusions
The PADME detector is currently under commissioning in the BTF experimental hall. First runs with beam and fully integrated sub-detectors and readout chain will take place in September 2018 for the final setup of the apparatus and the physics run will take place soon after. By the end of 2018 PADME plans to record a first sample of data to enter the exciting physics program of searches for low energy massive portals to the hidden sector of dark matter.

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