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The PADME experiment at LNF

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Abstract: The Positron Annihilation into Dark Matter Experiment (PADME) aims to search for the production of a dark photon in the process $e^+e^- \to A'\gamma$. It will use the 550 MeV positron beam provided by the DAΦNE LINAC impinging on a thin target. In case of annihilation, the accompanying ordinary photon is detected by the electromagnetic calorimeter regardless of the dark photon decay products. A single kinematic variable, the missing mass, characterizes the process, which should peak at $m_{A'}$ in case of A' production.

An overview of each component, and a description of the chosen technical solutions implemented to accomplish the experiment needs will be given.

Keywords: Calorimeters; Dark Matter detectors (WIMPs, axions, etc.); Diamond Detectors; Solid state detectors

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1 Introduction

The search for dark matter at accelerators has gained utmost attention in recent years. Astrophysical observations together with the lack of evidence of WIMPs or other heavy candidates led to the prediction of the existence of hidden sectors where dark matter is secluded. Massive photon-like particles in the MeV-GeV range could act as possible portals towards the hidden sectors. In one of the simplest formulation, they are vector bosons mediating a new interaction with the gauge symmetry $U_D(1)$. This dark photon A' may thus kinetically mix with the electromagnetic photon and be possibly produced in the same processes where the electromagnetic photon is produced.

The Positron Annihilation into Dark Matter Experiment (PADME) [1] aims at searching for the production of a dark photon in the process $e^+e^- \to A'\gamma$. It takes place at the Frascati National Laboratory of INFN, where it exploits the 550 MeV positron beam provided by the DAΦNE LINAC [2, 3], at the end of the Beam-Test Facility (BTF) transfer line.

2 PADME experimental technique

The main goal of the PADME experiment is to search for a dark photon produced in the annihilation of positrons of the beam and electrons at rest in the thin target:

$$e^+e^- \to A'\gamma$$

These experimental conditions allow to have a well-defined kinematics of the event and thus to obtain the mass of the missing state A' by combining the four-momenta of the incoming positron, of the rest electron and of the outgoing photon:

$$M^2 = (P_{e^+} + P_{e^-} - P_\gamma)^2$$

This is achieved by measuring the beam energy and divergence, the impact point in the target and the energy and position of the single photon in the final state. In this way PADME can probe A' masses up to 23.7 MeV/c^2 and the mixing parameter of the new interaction $\epsilon^2 > 10^{-6}$, with a total number of Positrons On Target (POT) of 4×10^{13}.

The main sources of background are the standard annihilation $e^+e^- \to \gamma\gamma(\gamma)$ and the bremmsstrahlung process $e^+N \to e^+N\gamma$. On top of this, the beam induced background and the beam halo particles must be considered as well.

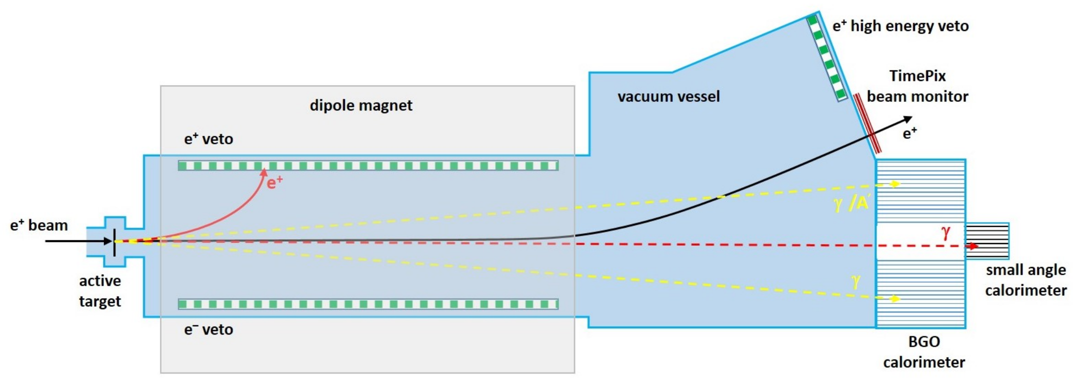

Figure 1. Outline of the PADME detector.

3 PADME detector

The topologies of signal and background processes have strictly driven the architecture of the experimental setup. The main components are (see figure 1):

- a thin active diamond target also capable of measuring the position and the intensity of the beam in each bunch;
- a beam monitor system made by two silicon-pixel detectors, the first can be inserted at the beam entrance, the second is located at the beam exit from the main vacuum chamber;

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- a dipole magnet to deflect the non-interacting positrons out of the detector acceptance and to allow momentum analysis;
- a veto system to identify charged particles in the final state and to measure their momentum;
- a calorimeter system to identify photons in the final state and to measure their energy and position;
- a vacuum vessel, encompassing the target, the flight path of the positron beam and photons up to the front face of the calorimeter system, and the veto detectors;

4 Positron beam

The PADME positron beam is provided by the S-band LINAC of the Frascati National Laboratory. Positrons are generated by hitting electrons accelerated by the first four sections of the LINAC on a W-Re target and then captured and accelerated by the second part of the LINAC up to 550 MeV. Then they can be either driven to a damping ring to be eventually injected into the DAΦNE collider, or transferred to the Beam Test Facility experimental hall, where the PADME apparatus is located. Alternatively, electrons accelerated by the LINAC (up to 750 MeV) can produce a secondary positron beam by showering on a Cu target, with a slightly higher maximum energy and different background conditions.

The beam structure is made by discrete bunches of particles of varable length with a rate of 50 Hz and can be adjusted in a wide range of energy, intensity, and divergence (see table 1).

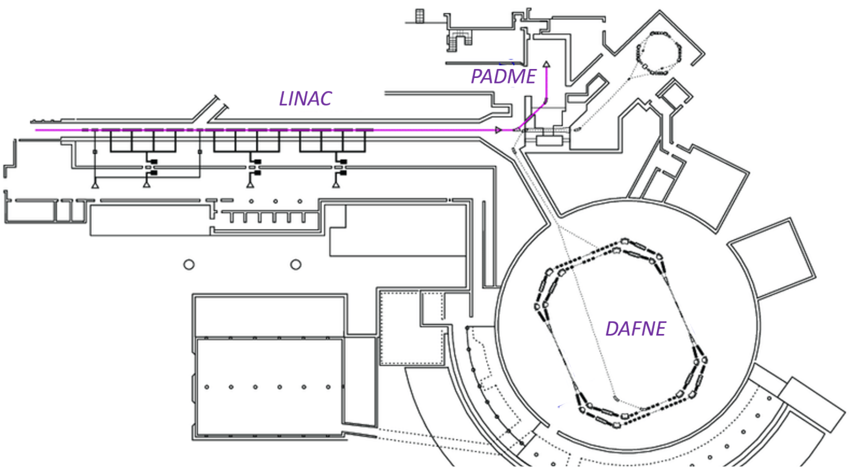

Figure 2. Layout of the Frascati accelerator complex.

5 Active target

It provides a target for the annihilation process, measures the XY profile of the beam and the beam multiplicity, i.e. the number of positrons contained in each bunch.

Table 1. Main characteristics of the LINAC.

Energy	up to 550 MeV
Bunch spacing	50 Hz
Intensity	1 ÷ 25k e^+/bunch
Bunch lenght	10 ÷ 200 ns
Beam spot	σ_{xy} ~1 mm
Divergence	~ 1 mrad

In order to have the highest possible annihilation over bremmsstrahlung cross-sections ratio, the lowest possible atomic number Z is required. Among the solid materials suitable for detection, diamond (Z=6) has been chosen. The sensor has an active surface of 20×20 mm^2 and a thickness of 100 μm [4]. 16 horizontal and 16 vertical readout strips are obtained with a graphite deposition on the diamond surface. The strips have 1 mm pitch and 0.15 mm of airgap interstrip. The sensor works inside the vacuum of the beam-pipe and is mounted on a printed circuit board that can be retracted from the beam-line in order to let the positrons in the PADME chamber without interaction, useful for calibration and monitoring purposes.

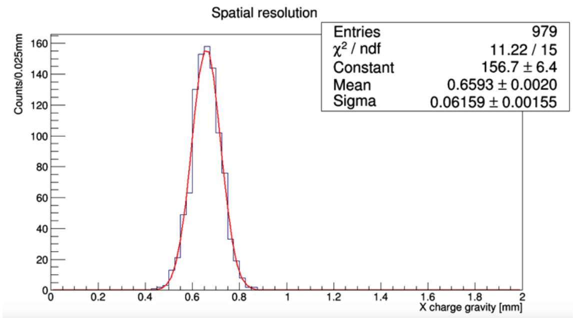

Figure 3. Spatial resolution of the target.

The position of the interacting positron is reconstructed with a resolution of 0.06 mm in both coordinates. The intensity of the beam is measured with a 10% error.

6 Charged particles veto

It provides suppression of the bremmsstrahlung background process.

There are 3 veto detectors, all composed by plastic scintillator sticks 10×10×178 mm^3, readout with a wavelength shifter fibre and a Hamamatsu Silicon photomultiplier with 3×3 mm^2 surface [5]. The electron and positron veto systems are placed inside the magnet just downstream of the beam target. They are modules of 96 and 90 sticks, respectively. Other 16 sticks are assembled to form the high-energy positron veto module, placed aside of the beam exit window, at the back of the vacuum chamber. All the three modules operate inside a vacuum of 10^{-5} mbar.

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The scintillators have a time resolution of 700 ps and an efficiency of 99% for charged particles with energy up to 500 MeV. The correlation between the position along the beam direction of the hit stick, and the momentum of the particle, allows to measure the latter with a resolution of 2%.

7 Calorimeters

The calorimeter system is composed by two distinct devices [6]. The Electromagnetic Calorimeter (ECAL) has the main goal of detecting annihilation events. It is a high resolution detector composed by 616 scintillating BGO crystals, each with dimensions of $21\times21\times230$ mm^3, and vacuum photomultiplier readout [7]. It is placed 3.45 m downstream the target and the whole radius of 29 cm allows an angular coverage between 15 and 84 mrad. BGO has high light yield, density and radiation length, but it is slow, having a decay time of 300 ns. To avoid the pile-up created by the copious bremmsstrahlung photons there is a 105×105 mm^2 square hole in the center of the ECAL, covered by the Small Angle Calorimeter (SAC).

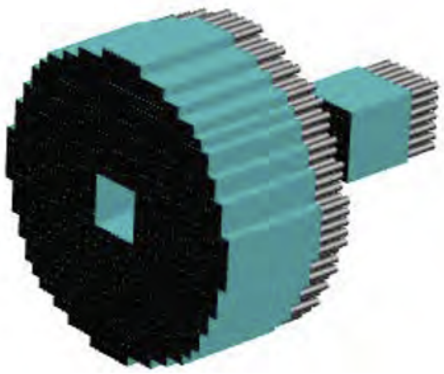

Figure 4. Outline of the calorimeters. The larger ECAL is upstream the beam, with a hole in the central part. The SAC is placed on the back, to detect the photons entering the hole.

The SAC has the goal of suppressing bremmsstrahlung events, by detecting the photons that are mostly radiated with and angle below 19 mrad. It is composed by 25 PbF_2 crystals operating by Cherenkov radiation emission. Each crystal is $30\times30\times140$ mm^3 and it is readout by a fast photomultiplier. The decay time of PbF_2 is 3 ns, resulting in a rate capability of 40 clusters per beam bunch.

8 Beam monitors

The first beam monitor is composed by two MIMOSA sensors [8] placed just in front and behind the target. The active area is 19.9×19.2 mm^2, covered by a 960×928 Silicon pixel array providing a single point resolution of 3μm. With two detection planes it provides the measurements of position, divergence and entrance angle of the beam. The MIMOSA is not used during normal data-taking, thus the retractable arm it is mounted on, allows to remove it from the beam line.

The second beam monitor is placed outside the vacuum chamber, in front of the exit window of the beam. It detects the positrons bent by the magnetic field which do not undergo any interaction in the target. It is a custom array, composed by a 2×6 matrix of Timepix3 sensors, each with an active area of 14×14 mm^2 covered by a 256×256 Silicon pixel array. It provides beam energy resolution and divergence, through the measurement respectively of horizontal and vertical width of the beam spot. The hit cluster counting also provides a second estimation of the Positrons On Target (POT) independent from the target.

9 Data taking

The Data Acquisition System is mainly based on the commercial digitizers CAEN V1742, 12 bit ADCs sampling the signals at 5 GS/s. There are three kind of triggers sent to the system to start the data acquisition: physics, given by the LINAC radiofrequency, cosmic muons, given by a scintillator telescope, and random. Whole signals are taken at Level0, while event merging and selection are performed at Level1, producing a data throughput of 10 MB/s.

The first PADME run has been fulfilled between October 2018 and February 2019, collecting 7×10^{12} Positrons On Target. This data volume has been mostly used for beam optimization, background studies, and detector calibration.

A second physics run is foreseen during 2020. The final goal is to collect 4×10^{13} POT in order to reach the desired sensitivity on the measurement of the dark photon mixing parameter.

10 Future programs

A possible future upgrade of the experiment considers to use the DAΦNE positron ring to create a high quality beam followed by a slow extraction through channelling in a bent crystal towards the PADME detector [9]. Bunch length between 1 ms and 1 s are feasible in this operation mode, thus improving the number of POT by a factor 10^4 and the sensitivity of physics parameters of 10^2.

Another option is to use PADME to scrutinize the anomaly found by the ATOMKI group described in [10], drawing great attention in recent months. The hypothetical new boson dubbed X17 could be resonantly produced with a 282 MeV positron beam on a target, well within the PADME capability. In this case both the LINAC configuration and the detector should be modified. The former with longer positron pulses and higher intensity [11], the latter with a thicker target and a spectrometer suitable to detect visible decays in the final state.

11 Conclusions

The PADME experiment started to explore the dark sector using for the first time the missing mass technique on an extracted positron beam to search for a dark photon in annihilation processes. The detector has already collected 7×10^{12} POT, used for the commissioning and the optimization of the beam line. The design performance has been demonstrated to be successfully achieved. The final goal is to collect 4×10^{13} POT in two years of running, allowing to reach a sensitivity on the measurement of the dark photon mixing parameter of the order $\epsilon \sim 10^{-3}$.

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