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Performance of the charged particle detectors of the PADME experiment

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Abstract: PADME (Positron Annihilation into Dark Matter Experiment) is searching for the production of a dark photon from positron-electron annihilation $e^+e^- \rightarrow \gamma A'$ using the positron beam of the Beam Test Facility (BTF) of the DAΦNE Linac at Laboratori Nazionali di Frascati (LNF). This work presents the assembly and the performance of the charged particle veto system required to identify Bremsstrahlung processes which are the main source of background events.

Keywords: Dark Matter detectors (WIMPs, axions, etc.); Detector alignment and calibration methods (lasers, sources, particle-beams); Scintillators, scintillation and light emission processes (solid, gas and liquid scintillators)

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Contents

1 The physics motivation of the PADME experiment

The strong, weak and electromagnetic interactions are described with high precision by the standard model (SM) of particle physics. Nevertheless, the existence of dark matter, demonstrated by cosmological and gravitational observations, is a compelling motivation to go beyond the SM. The lack of experimental evidences of dark matter particle candidates at the electroweak scale has driven the attention of the whole scientific community to the introduction of a so called dark sector [1], which can only faintly interact with the SM particles through a neutral portal. The simplest model just introduces one extra U(1) gauge symmetry and the corresponding massive gauge boson is called Dark Photon A' [2]. One of the simplest mechanisms that could determine weak couplings between SM particles and the A' field is the kinetic mixing, between the gauge bosons of the two U(1) symmetries described by the kinetic term in the lagrangian:

$$L_{\text{mix}} = -\frac{\epsilon}{2} F^{\text{QED}}_{\mu\nu} F^{\mu\nu}_{\text{dark}},$$

where a low value of the mixing parameter ϵ (below 10^{-3}) could justify the lack of experimental evidence for such scenario so far. PADME is a fixed target experiment located at the Beam Test Facility (BTF) [4] at the Laboratori Nazionali di Frascati (LNF) which uses a positron beam of energy up to 550 MeV.

The PADME experiment [3] searches for the dark photon A' in the process $e^+e^- \to \gamma A'$ using the missing mass method, which is independent from the new gauge boson decay mode. The missing mass squared is computed by the formula:

$$M^2{}_{\text{miss}} = (P_{e^+} + P_{e^-} - P_\gamma)^2,$$

where P_{e^+}, P_{e^-} and P_γ are the 4-momentum of the positron beam, of the target electron and of the emitted photon, respectively. PADME is sensitive to value of ϵ up to 10^{-3} for a mass of the dark photon below 23.7 MeV/c^2 with 4×10^{13} Positrons On Target (POT).

2 The PADME detector

The PADME detector (schematically shown in figure 1) is made of a thin diamond target, a magnetic dipole, which sweeps the beam out of the experimental acceptance, a high resolution electromagnetic calorimeter (ECAL), a fast small angle electromagnetic calorimeter (SAC) and a charged particle veto system.

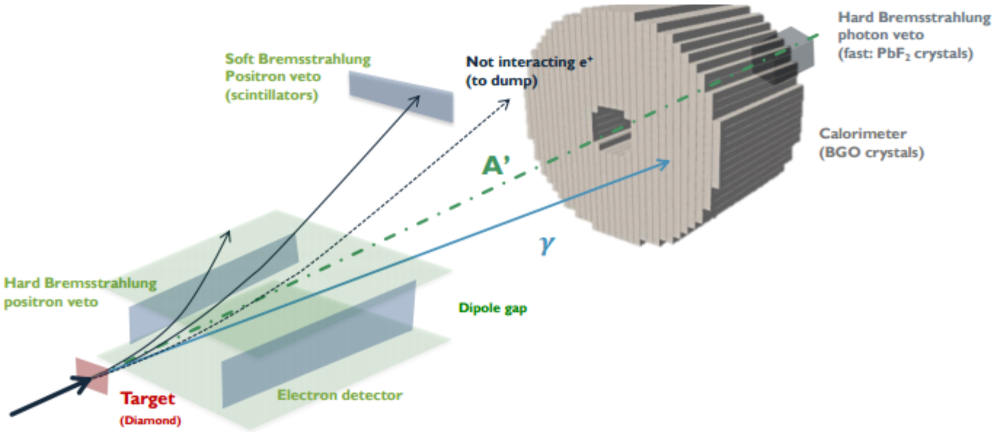

Figure 1. Layout of the PADME detector. The positron beam of energy up to 550 MeV hits the target. The signal is represented by a cluster in ECAL due to a single SM photon, emitted in coincidence with a dark photon. The non-interacting beam goes to the beam dump; SM physics processes like the annihilation in two (or three) photons and Bremsstrahlung are the main source of background.

The diamond target of $2 \times 2\,\text{cm}^2$ area and thickness $100\,\mu\text{m}$ is hosted in the vacuum vessel, together with the charged particles veto system. ECAL, the main detector of the experiment, is made up of 616 BGO crystals arranged in a barrel with a central hole to avoid the high rate of forward Bremsstrahlung photons. The SAC, a matrix of 5×5 PbF_2 crystals, is placed just behind the hole of ECAL and is capable to stand a high particles rate.

A positron that hits the target could annihilate and produce together a SM and a dark photon; a signal event is represented by a ECAL cluster, due to the hit of the SM photon and no other in-time hits in the detector.

2.1 The role of the veto system

The main source of physics background in PADME is the Bremsstrahlung process that could produce a single photon in the final state in ECAL, mimicking a signal event, combined to a positron of energy lower than the beam energy by an amount corresponding to the energy of the photon. A system of vetoes has been inserted in the experiment to reject these processes, detecting the positron emitted in coincidence with the photon. It consists of two detectors: the Positron Veto (PVeto), which is about 1 m long and covers the left internal vertical wall of the vacuum chamber inside the PADME magnetic dipole, and a High Energy Positron (HEP) veto, which covers a small angular region between the beam dump and the PVeto, covering the positron momentum range ($450 < P_{e^+} < 550$) MeV/c. An Electron Veto (EVeto), identical to the PVeto, is placed on the internal right vertical wall of the vacuum chamber inside the magnet. The PVeto and the EVeto may also be used to search for the hypothetical dark photon decays in the visible channel. A good time resolution, below 1 ns, and high efficiency are required for the veto system to allow Bremsstrahlung events identification.

Other sources of background of the experiment could be the annihilation into two (or three) SM photons, which could emulate the dark photon production signal in case a single photon is detected. This background, of course, could not be rejected using the veto system of the charged particles.

3 Veto system parameters

The charged particle veto system is made up of 3 arrays of 90, 96 and 16 scintillating bars for PVeto, EVeto and HEP Veto respectively. An aluminum support structure holds these arrays of bars rotated around their longitudinal axis by 0.1 rad to minimize geometrical inefficiencies, together with the Front End Electronics (FEE) boards, each one serving up to four channels. The scintillating bars of size $10 \times 10 \times 178\,\mathrm{mm}^3$ are made of a plastic polystyrene-based material with 1.5% concentration of POPOP and they are produced by UNIPLAST. A longitudinal $1.3 \times 1.3\,\mathrm{mm}^2$ groove houses an optical wavelength shifter (WLS) fiber BCF-92 glued with Eljen EJ500 optical epoxy cement. The BCF-92 fiber has a maximal emission wavelength at 492 nm and maximal absorption wavelength at about 400 nm (matching the POPOP emission spectrum). Silicon photo-multipliers (SiPMs) Hamamatsu 13360, which are able to work in vacuum and sustain a magnetic field of about 0.6 T, allow the conversion of the photons into electric signals. Low cost and low operating voltage are also good features that supported this choice for the final assembly in the experiment. The scintillating bars of the HEP Veto have SiPM readout at both edges, top and bottom.

3.1 Veto system prototype and beam test

A prototype of the veto detector was assembled and tested in April 2017 with a 500 MeV single electron beam of the DAΦNE LINAC at the BTF [5]. It consisted of 16 bars with the same geometrical parameters of the final detector of the experiment but different SiPMs (Hamamatsu S12572, more noisy than the final chosen, the 13360). During the beam test, the front-end signals were digitized by a CAEN module V1742, the same of the final readout, at the rate of 5 GS/s. The time resolution and the efficiency were studied varying the distance between the impact point of the beam with respect to the photodetectors, studying different light collection configurations. The beam test also set an upper value for each scintillator noise, defined as the number of events with no particles passing through the bars which still show signals, below 1%.

Readout performed collecting both the scintillator and the fiber light showed the best performance, with a time resolution down to 600 ps and inefficiency lower than per mille; therefore, this solution was chosen for the final veto detectors.

3.2 The assembly of the vetoes in the experiment

All the veto detectors were installed in the experiment in September 2018 and were operated until the end in February 2019. In figure 2 the final assembly of the vetoes inside the internal vacuum chamber is shown. The PVeto and EVeto bars are positioned inside the internal vacuum chamber in the magnet dipole, with the long side parallel to the magnetic field direction, while the HEP Veto is located between the PVeto and the ECAL region, near the beam dump.

During Run I of the experiment, the Front End-Electronics (FEE) of PVeto and EVeto operated in vacuum, in a stationary magnetic field of about 0.45 T.

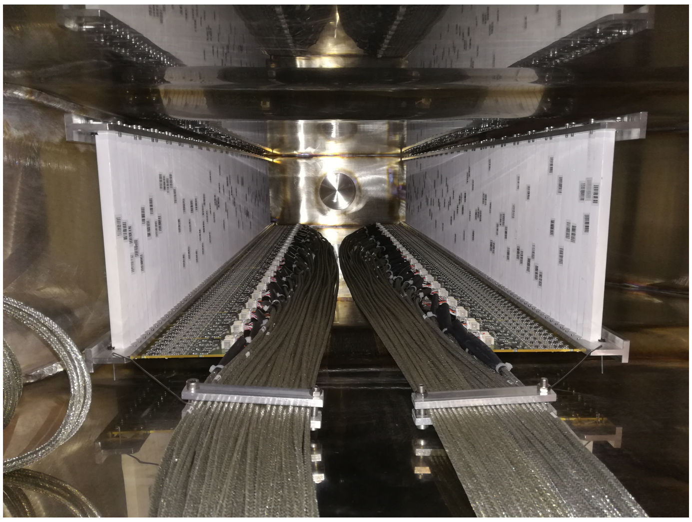

Figure 2. View of the internal vacuum chamber, just before the final assembly. The EVeto (on the left) and the PVeto (on the right) are shown. The beam comes from the front.

4 Preliminary results

The data taking performed so far allowed to achieve first milestones regarding the Bremsstrahlung and annihilation events identification [6]. In the following sections preliminary results related to the veto detectors such as the evaluation of the time resolution and first Bremsstrahlung studies are presented.

It is useful to underline that the assignment of the Channel Id to the veto bars, which is a pure convention, is such that Channel Id increases with the Z position of the bar (i.e. with the distance from the target).

4.1 Signal reconstruction

An event recorded by the PADME detector corresponds to the signals produced by the interactions of about 20 k positrons[1] in a time interval of 200 ns. The external trigger is provided by the BTF, which can deliver up to 50 bunches of positrons per second. One out of these bunches is sent to a hodoscope

[1]This is the mean beam multiplicity. In each run the multiplicity can vary, from 17 to 25 k particles, depending on the beam conditions.

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for the measurement of the beam energy, which for positrons, can reach 550 MeV. The veto signals during data taking were digitized by CAEN V1742 at 2.5 GS/s and reconstructed through a multi-hit algorithm. The pedestal was calculated from the mean of the first 200 samples and then subtracted to the initial waveform. An example of a veto signal after pedestal subtraction is shown in figure 3.

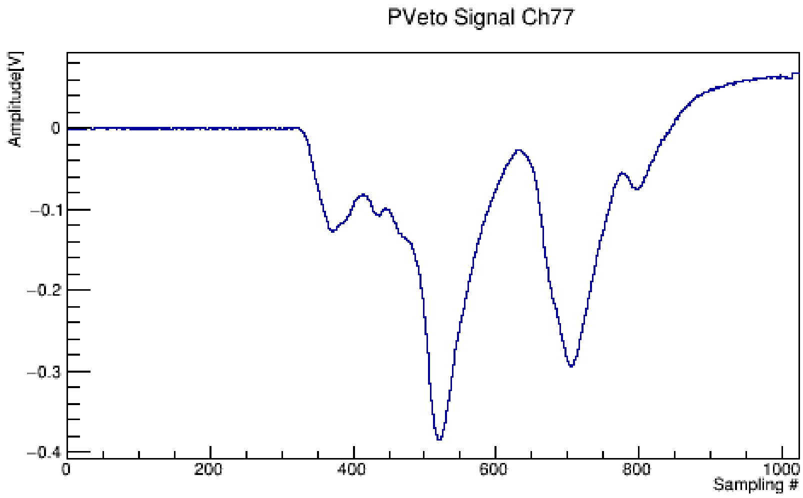

Figure 3. Example of a PVeto signal for a random channel after pedestal subtraction.

A multi-hit reconstruction was performed using the TSpectrum algorithm, a one-dimensional peak search function of the ROOT [7] library. The position and height of each peak provide physical informations to store for the analysis, representing the time and amplitude of the hit. This last quantity is directly proportional to the energy released by the positron in the scintillator. Before doing any kind of analysis, it is important to obtain absolute calibration constants that ensure the equalization of the vetoes channels response. This absolute calibration was performed evaluating the energy distribution of hits of each electronic channel of the vetoes, setting a very low threshold for the hit reconstruction. A Gaussian fit allowed to estimate the mean value of the pulse height distribution and the absolute calibration constants were calculated forcing a mean pulse height of 50 mV, as follows:

$$\mathrm{CC}(i) = 50\,\mathrm{mV}/\mathrm{Mean}(i),$$

where the index i stands for one of the veto channels.

The PVeto hit energy distribution after calibration for 10000 events is shown in figure 4. In addition a Landau fit is superimposed, which gives a Most Probable Value $\simeq 51.8$ mV as expected, thanks to the absolute calibration.

4.2 Time resolution

The difference in time between the PVeto hits and hits in the central SAC crystal can provide a first estimate of the time resolution of the vetoes, assuming that the time resolution of the fast calorimeter in comparison to the PVeto is negligible. The sigma of a Gaussian fit gives the time resolution, of about 670 ps. The measured time resolution is in line with the experiment requirement, demanding a value lower than 1 ns (see section 2.1).

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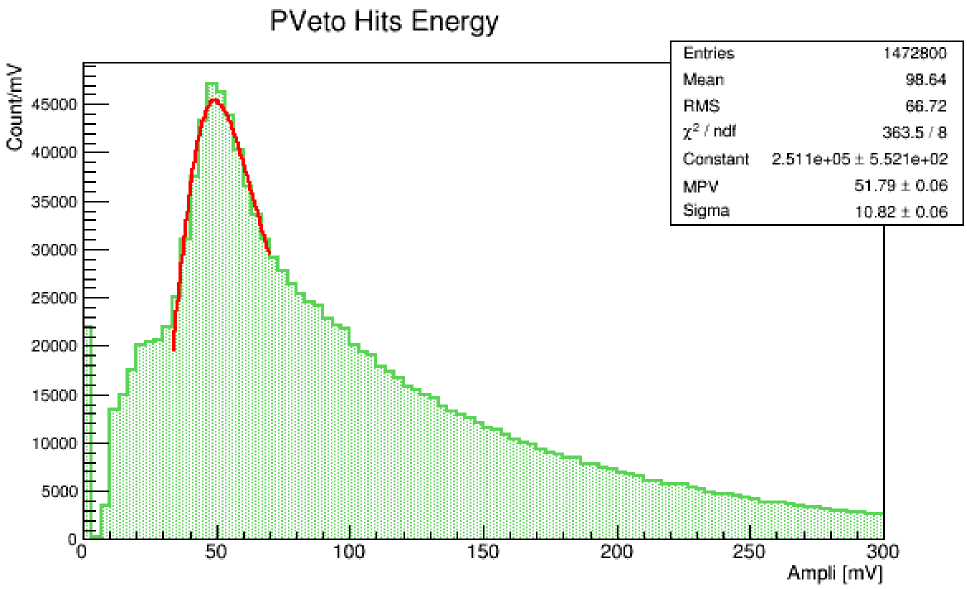

Figure 4. Positron Veto signal pulse height distribution for 10000 events. A Landau fit is superimposed, which gives a Most Probable Value of about 51.8 mV.

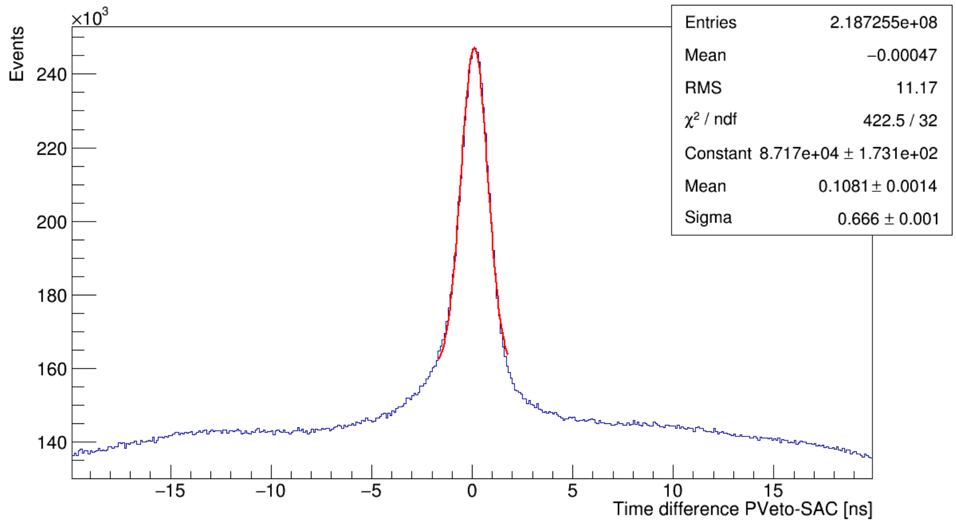

Figure 5. Time difference between the PVeto hits and the hits of a single SAC central crystal. The sigma value of the gaussian fit superimposed gives an estimate of the time resolution ($\sigma_t \simeq 670$ ps).

4.3 Bremsstrahlung interactions

As seen in section 2.1, a positron of the beam could interact with the target, emitting a photon which could hit both the ECAL and, most often, the SAC. In this preliminary study, only emitted photons that hit the SAC were considered. A further study that will include also ECAL clusters is needed to have a complete understanding of the background of the experiment, increasing the sensitivity of the future dark photon analysis.

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A Bremsstrahlung event fulfills the request of time coincidence between the PVeto and SAC cluster, as follows:

$$|\, t_{\text{cl PVeto}} - t_{\text{cl SAC}} \,| < 1\,\text{ns}\,,$$

and it satisfies also the energy constraint $E_{e^+} + E_\gamma = E_{\text{beam}}$.

In this analysis the events are labeled as *Bremsstrahlung candidates* since no energy constraint was requested. For the preliminary study, the time alignment of the PVeto was performed taking the SAC central crystal as reference and determining the time shifts for each channel with respect to that. In addition, the energy calibration of the SAC was needed, in order to have a gain equalization of the detector. Figure 6 shows a clear correlation between the SAC cluster energy from the emitted photon and the channel identifier of the PVeto cluster seed,[2] related to the kinetic energy of the slowed down positron, after the subtraction of the out-of-time background.

A high energy photon in the SAC corresponds to a low energy positron that hits first PVeto bars with low Z (or Channel Id of the cluster seed); conversely, a high energy positron emitted with a low energy photon hits the last Channel Ids of the PVeto.

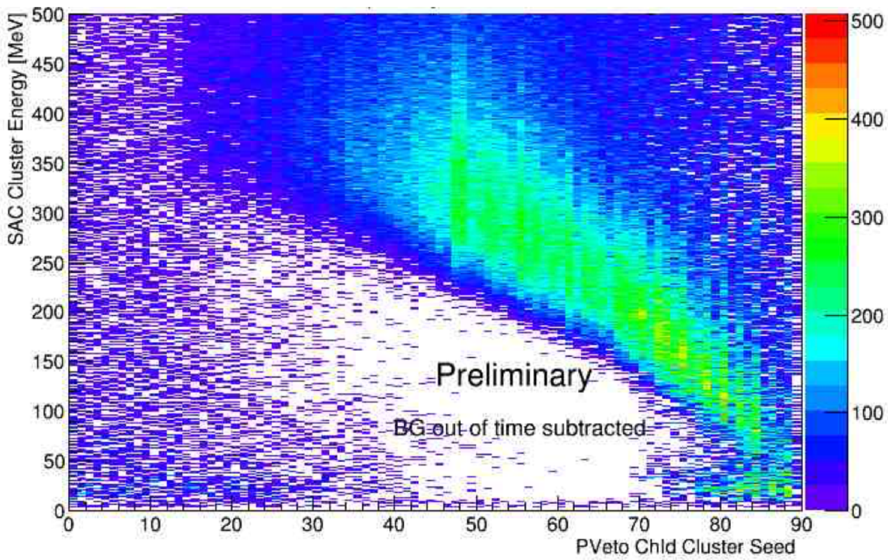

Figure 6. SAC cluster energy as a function of the PVeto cluster position for $\Delta t < 1$ ns. A clear correlation between the SAC cluster energy and the Channel Id of the cluster seed, proportional to the Z position of the PVeto in the PADME frame, is shown. Beam energy 490 MeV, 11M POT.

5 Conclusions

The PADME data taking performed so far allowed the collaboration to understand the behavior of the whole detector, achieving the identification of SM physics processes, such as annihilation and Bremsstrahlung events. In particular, this work shows the preliminary performance of the veto system. The charged particle veto system worked inside the PADME experiment in stable conditions

[2]The seed is the most energetic channel hit, that is the one which has the highest amplitude between its neighbours, from which the clusterization starts.

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during the whole Run I since September 2018 until the end of February 2019. A time resolution below 700 ps was achieved, satisfying the requirement of the experiment (< 1 ns). Preliminary studies showed that the detector is able to make a good identification of Bremsstrahlung candidate events.

The Run II of the experiment, scheduled for the beginning of next year, will allow to better understand the detectors behavior and increase statistics to perform the final analysis, searching for the dark photon.

Acknowledgments

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