NEW LIGHT PARTICLE SEARCHES WITH PADME*

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The PADME experiment at Laboratori Nationali di Frascati is designed to study possible dark matter explanations relying on the presence of a light particle that acts as a mediator between the visible and the hidden sectors. Three data-taking runs have resulted in the collection of more than 10^{13} positrons-on-target. The experimental setup was initially designed to the search for associate dark photon production and later modified for the search for resonant production of a new $X17$ particle, originally proposed by the ATOMKI Institute. The setup for the different runs, the data taking, and background studies are presented, as well as the first physics results and the prospects for the next run of PADME.

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1. Introduction

The need for an explanation of the dark matter phenomenon has led to the development of different hypotheses for expanding the Standard Model. Many of them rely on the existence of a "hidden sector" of particles, which interact with visible matter through mediators. One such proposed mediator is the dark photon A' which corresponds to a vector field, similar to that of the photon [1]. The main properties of the dark photon are its mass $m_{A'}$ and its coupling ϵ to the Standard Model fermions. The interaction between A' and visible matter can thus be described by introducing a new $\mathrm{U}'(1)$ gauge symmetry, similar to the electromagnetic

$$\mathcal{L} = \epsilon \bar{\psi}_f \gamma_\mu \psi_f A'_\mu \,. \tag{1}$$

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An important discovery that might further back up the proposed dark photon hypothesis is the anomalous distribution of the opening angle of the e^+e^- pairs, produced by internal conversion in ^{8}Be decays. This can be explained by the existence of an intermediate state with $M_X \approx 17$ MeV [2].

PADME (Positron Annihilation into Dark Matter Experiment) [3] is located at the Beam Test Facility (BTF) of the DAΦNE [4] accelerator at Laboratori Nationali di Frascati. It studies the annihilation of accelerated beam positrons with energies up to 550 MeV and electrons in a fixed thin target. The setup of the experiment for Run I and Run II was designed to search for associate production of a dark photon A' and a visible photon γ

$$e^+e^- \to A'\gamma\,. \tag{2}$$

The experiment employs the missing mass technique, knowing the 4-momenta of the beam positrons and the target electrons, and using the position and energy data to calculate the 4-momentum of the produced photon

$$M^2_{\rm miss} = (P_{e^+} + P_{e^-} - P_\gamma)^2\,. \tag{3}$$

For Run III the PADME setup was modified to search for resonant $X17$ production and identifying it by its subsequent decay to an e^+e^- pair.

2. PADME Run I and Run II

The experimental setup for Run I and Run II is shown in Fig. 1. PADME uses a positron beam provided by the DAΦNE linear accelerator. It delivers positrons in bunches with a 50 Hz rate, each bunch containing $\approx 2 \times 10^4$

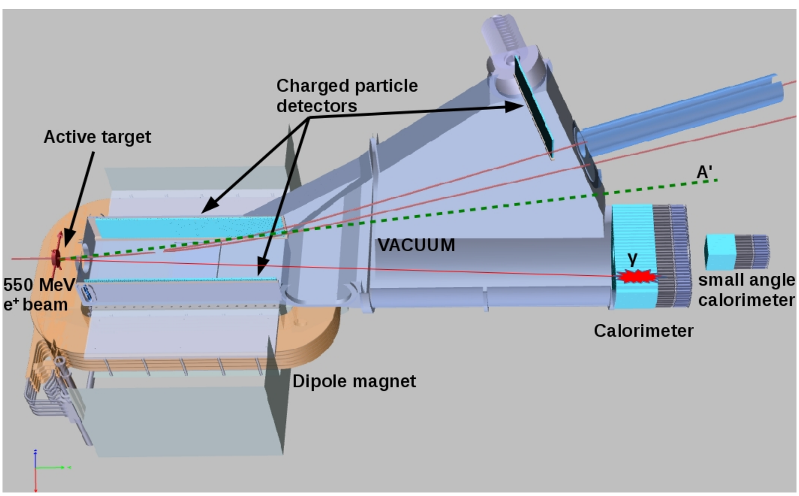

Fig. 1. Schematic view of the PADME setup for Run I and Run II of data taking.

positrons with a typical duration of 200–300 ns. The maximum beam energy is 550 MeV which can be achieved by placing a copper target on the BTF line (so-called secondary positron beam).

The PADME active target [5] is composed of a 20 cm $\times$ 20 cm $\times$ 100 μm polycrystalline diamond with 16 horizontal and 16 vertical 1 mm wide graphite electrodes engraved on both of its sides. The electrodes allow the target to serve both as the medium for the annihilation and a detector, monitoring the beam x and y coordinates and its multiplicity bunch by bunch.

The charged particle detector system of PADME [6] consists of a positron detector (PVeto) and an electron detector (EVeto) placed inside the magnet, and a high-energy positron detector (HEPVeto), placed next to the beam exit window. The PVeto can register non-interacted beam positrons with momenta in the 50–450 MeV range, while the HEPVeto registers positrons above 450 MeV.

The PADME Electromagnetic calorimeter (ECal) [7] is placed 3.45 m downstream from the target and is composed of 616 BGO scintillating crystals, each measuring $2.1 \times 2.1 \times 23$ cm^3. A hole in the central region of the ECal allows most of the photons emitted in Bremsstrahlung events to pass through and be registered by the Small Angle Calorimeter (SAC) [8], located behind the ECal. The faster decay time of the signals in the SAC makes it suitable for covering this central region, where the number of incident photons is high.

A TimePix3 silicon pixel detector array [9], placed on the path of the non-interacting positrons at the beam exit window, is used for additional monitoring of the beam spread and multiplicity.

The data taking for PADME Run I was done in 2018 and 2019 with two different beamline setups. The initial setup used a secondary beam and recorded $\approx 7 \times 10^{12}$ positrons on target before changing the setup and using the primary beam, produced by the LINAC positron converter. During Run I, data quality evaluation, detector calibration, and performance checks were performed.

The PADME Run II data taking took place in 2020 using the primary positron beam and collected 5×10^{12} positrons on target.

Bremsstrahlung, two- and three-photon annihilation, and Bhabha scattering are the main contributing processes to the background in PADME.

Bremsstrahlung $e^+N \to e^+N\gamma$ results in a single photon registered by the detector and therefore needs to be filtered when analyzing single-photon events in search for A'. These photons typically have low energies which results in this process dominating the high missing masses. The especially high beam multiplicity ($\approx 3 \times 10^4$ positrons per bunch) and short bunch duration time for Run II result in the need for reliable event reconstruction for matching the Bremsstrahlung photons with the low-energy positrons registered by the PVeto. A machine learning algorithm using convolutional neural networks [10] was developed with the task of reconstructing the arrival times and amplitudes of the individual pulses, with the initial results showing ≈ 500 ps time resolution. The trained model was introduced to the experiment reconstruction and its performance was evaluated by selecting and analyzing two-photon annihilation events, and comparing the results to the ones obtained with the conventional experiment reconstruction method [11].

The PADME Run II data was used for precise measurement of the two-photon annihilation cross section $\sigma(e^+e^- \to \gamma\gamma)$. This presents the first measurement of the cross section at sub-GeV energies with more than 20% accuracy. The result was obtained at a beam energy of 430 MeV using a tag-and-probe method that combines the energy and angle information for the registered photons: in the analysis of two-cluster events, one photon is used as a tag photon, and then the probe photon is searched for, knowing its supposed position and energy. The obtained value for the cross section is

$$\sigma(e^+e^- \to \gamma\gamma(\gamma)) = 1.930 \pm 0.018(\mathrm{stat.}) \pm 0.119(\mathrm{syst.})\ \mathrm{mb}\ [12]\,.$$

This is the only measurement in this energy range using a method that observes the two final-state photons. It allows for the determination of the detector efficiency and is an important part of the dark photon search.

3. Searching for $X17$ with PADME in Run III

The $X17$ particle is a proposed solution to the anomaly in the opening angle of e^+e^- pairs resulting from the internal pair production in the de-excitation of ^{8}Be nuclei. This anomaly was first observed by the ATOMKI Institute and later also confirmed in ^{4}He [13] and ^{12}C [14] nuclei experiments. The resulting values for the opening angle show a 6.8σ bump and can be explained by the presence of an intermediate particle decaying into the e^+e^- pair, with the kinematics being determined by the new particle mass. Experimental results both for ^{8}Be and later for ^{4}He and ^{12}C nuclei point to an approximate mass of 17 MeV/c^2.

The PADME experiment is sensitive exactly in the mass range to which the $X17$ particle belongs, which presents a good opportunity to use the setup in the search for this new state. A new run in 2022 was performed, dedicated to resonant $X17$ production and its subsequent decay into an e^+e^- pair

$$e^+e^- \to X17 \to e^+e^-\,. \tag{4}$$

This would be shown by observing a higher number of the e^+e^- pairs at beam energies corresponding to $\sqrt{s} = M_{X17}$. The main contribution to the background for Run III is s-channel and t-channel Bhabha scattering.

The PADME experimental setup was modified before the beginning for Run III in order to allow for the detection of the e^+e^- pairs. The beam multiplicity was reduced in order to lower the rate of Bremsstrahlung events and a scan was performed at beam energies around 283 MeV with a total of 10^{10} positrons on target collected.

Since the charged particle detectors cannot be used to detect electrons and positrons coming from such decays, the magnetic field was switched off and the ECal was used for registering the particles. In order to be able to properly identify the e^+e^- pairs and distinguish them from two-photon annihilation events, an additional detector comprised of an array of plastic scintillators was placed in front of the calorimeter to act as a charged particle tagger. The event selection includes identifying two-cluster events and using a tag-and-probe method to determine the selection efficiency. For the precise beam monitoring, the TimePix3 array was moved behind the ECal, and an additional lead glass block was placed behind it to perform independent measurement of the positron flux.

The expected sensitivity of PADME for Run III, obtained using the CLs method on Monte Carlo data, is shown in Fig. 2.

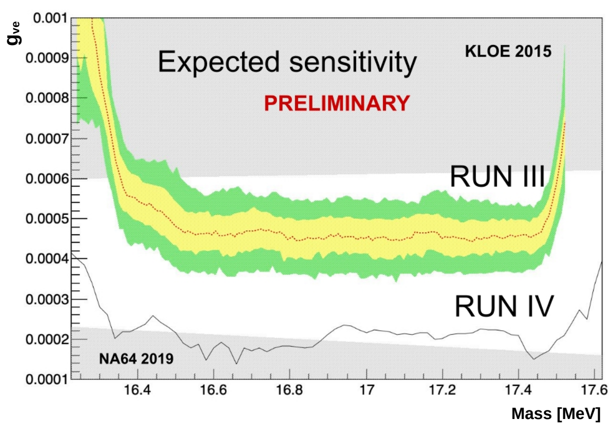

Fig. 2. Expected sensitivity of PADME Run III and Run IV in the $X17$ parameter space with 90% confidence level, based on Monte Carlo studies. The 1σ uncertainty is shown with the yellow band band, while the 2σ is in green.

4. Future prospects

The results from PADME Run III will be dominated by the positron-on-target systematics and the ECal acceptance. This leads to the need to explore different methods to mitigate or cancel some of the systematic effects for PADME Run IV. One solution is to exploit a normalization channel with the same two-body kinematics as the $X17 \to e^+e^-$ decay. A natural candidate for that is two-photon annihilation $e^+e^- \to \gamma\gamma$, which points to the requirement for good separation between charged and neutral states in order to precisely determine the $N_{e^+e^-}/N_{\gamma\gamma}$ ratio. For that reason, a new micromegas chamber will be installed in front of the ECal to serve as a charged particle tagger. It will also allow for additional control of the positrons-on-target by using variable high voltage depending on the distance from the beam center and measuring the beam multiplicity at the lower voltage central region.

5. Conclusion

The PADME experiment at Laboratori Nationali di Frascati is searching for new light particles as possible mediators between the visible and the hidden sector. The first two runs were dedicated to the possible associated production of a Dark photon A' alongside a visible photon. The data was already used to measure the multiphoton annihilation cross section in a previously unexplored energy range with good accuracy. The third run, dedicated to the search for resonant production of the new hypothetical $X17$ particle, was performed and a detailed study of the relevant systematics is undergoing. A future fourth run of the experiment will explore strategies for mitigating systematic effects and achieving better event selection abilities by introducing a new detector.

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