In search of new particles with PADME

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Several contemporary particle physics experiments at accelerators aim to contribute in the quest to describe the properties of the Dark matter by looking for new particles. One of them is the Positron Annihilation into Dark Matter Experiment (PADME), at the Laboratori Nazionali di Frascati of INFN. Its main goal is to search for a Dark Photon (A') by studying the annihilation of beam positrons on a fixed target. Since 2018, two data taking periods were completed successfully, collecting O(10^{13}) positrons on target. In 2022 the detector setup was then modified to explore the existence of the so-called "X17" particle, postulated to explain an anomalous effect observed by the ATOMKI collaboration. In this paper the PADME experiment is presented, the main results and the possible future prospects are discussed.

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1. Introduction

The search for a fundamental theory to describe the nature continues. Despite the great success of the Standard Model (SM), several problems still remain unsolved. Examples include the lack of anti-matter in the Universe, the anomalous magnetic moment of the muon and the constituents of the Dark Matter (DM). Some models [1] try to solve the puzzle by introducing new dark sector of particles in which the heavy DM particles interact with the SM particles via a so-called portal. These models suggest that the portal can be a vector dark photon (A'), a pseudo-scalar axion-like particle (ALP), a scalar dark Higgs or a fermion particle. Two parameters are characteristic for both A' and ALP models – the mass of the portal particle (M) and its coupling constant (ϵ) to SM particles. The relevant phenomenology for experimental searches of such particles are the following:

- If the portal is the lightest particle in the dark sector it can only decay visibly, e.g. if $M > 2M_e$ to an e^+e^- pair;
- If the portal is not the lightest particle in the dark sector it can decay invisibly and thus escape detection.

The Positron Annihilation into Dark Matter Experiment (PADME) [2] located at Laboratori Nazionali di Frascati, INFN, is a fixed target experiment that searches for dark sector portals. It is using a positron beam provided by the DAΦNE accelerator complex. The beam is impinging on a thin diamond target. The process of interest is an annihilation reaction $e^+e^- \rightarrow \gamma + X$, where γ is the SM photon and X is a dark sector portal (either A' or ALP). A missing mass technique is used to determine the mass of the dark sector portal:

$$M^2_{miss} = (P_{e^+_{beam}} + P_{e^-} - P_\gamma)^2, \tag{1}$$

where M^2_{miss} is the squared mass of the dark sector portal, $P_{e^+_{beam}}$ is the positron beam 4-momentum, P_{e^-} is the 4-momentum of the atomic electrons of the target and P_γ is the measured 4-momentum of the recoil γ. A peak in the distribution of the missing mass will be an indication for the existence of a portal.

2. PADME detector

The PADME experiment is using a positron beam provided by the DAΦNE LINAC. The maximum energy of the positrons is 550 MeV. This limits the sensitivity of the experiment to dark sector portals masses to less than 23.7 MeV/c^2.

A schematic view of the PADME experiment is given in Figure 1. The positrons from the beam interact within a 100 μm thick diamond target [3], which acts also as a detector and measures the beam intensity and impact position. At a distance of 3.46 m from the target is located the main detector of the experiment – the electromagnetic calorimeter (ECal) [4]. It has a ring shape and is composed of 616 BGO scintillating crystals with dimensions $2.1 \times 2.1 \times 23.0$ cm^3. The main background source is due to hard Bremsstrahlung photons emitted at low angles with respect to the beam. To collect such signals, a detector with faster response is placed behind a central hole

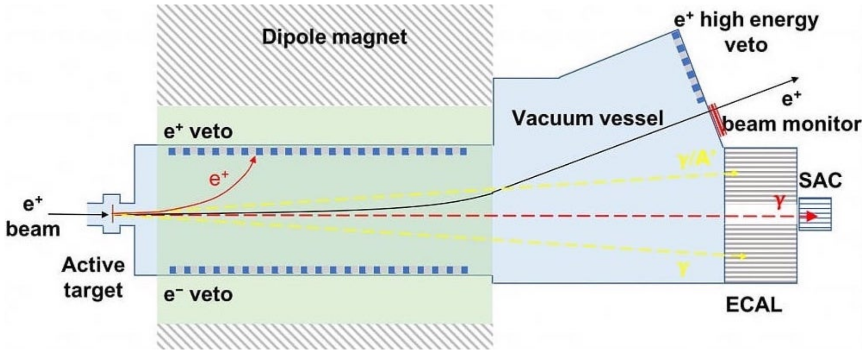

Figure 1: PADME detector system.

in the ECal – the Small Angle Calorimeter (SAC). It is made of 5×5 PbF_2 crystals [5], arranged in a square matrix. In addition, inside a vacuum vessel, electron and positron veto detectors are placed [6]. They are made of scintillating bars with BCF-92 WLS fibers coupled to Hamamatsu S13360 SiPMs. A dipole magnet provides a 0.5T magnetic field to deflect charged particles with momentum less than 450 MeV/c to the vetoes. An additional veto detector is placed close to the outgoing beam to detect positrons with momentum up to 500 MeV/c. The Bremmstrahlung photons are matched by time coincidences with their corresponding positrons which are registered by the veto system. In this way significant background reduction is performed. To monitor the beam at the end of the PADME setup, a TimePix3 silicon pixel detector is used.

3. PADME studies and future prospects

3.1 Measurement of the cross-section of electron-positron annihilation into photons

The described setup was used during two data taking periods – Run I and Run II. About 10% of the acquired data were used to measure the inclusive in-flight annihilation cross section $\sigma(e^+e^- \to \gamma\gamma(\gamma))$ with a precision of $\sim$ 5% [7]. The result, $\sigma(e^+e^- \to \gamma\gamma(\gamma)) = (1.977 \pm 0.018_{stat} \pm 0.119_{syst})$ mb, is consistent with the SM predictions and for $E_{beam} < 1$ GeV it is the most precise measurement with two photons tagging. This result is also an important step for the further dark particle searches, validating the performance of the experiment.

3.2 X17 particle studies

In 2016 the ATOMKI collaboration observed an unexpected bump in the angular distribution of the emitted e^+e^- pairs from excited ^{8}Be nuclei decays [8]. In more recent studies, the collaboration presented results with improved setup, using decays of ^{4}He [9] and ^{12}C [10], where the anomaly was observed as well. In all of the three cases a new particle with mass $\sim$ 17 MeV decaying to e^+e^- pair could explain the bump.

The X17 proposed mass is exactly in the sensitivity range of the PADME experiment, as can be seen in Figure 2. This provides a unique opportunity for the experiment to take part in the X17 investigation. For this purpose a technique using resonance X17 production was developed. An increase of several orders of magnitude in the production rate of e^+e^- pairs when the positron beam energy fulfils the relation $\sqrt{s} = M_{X17}$ will correspond to the resonant production of the X17

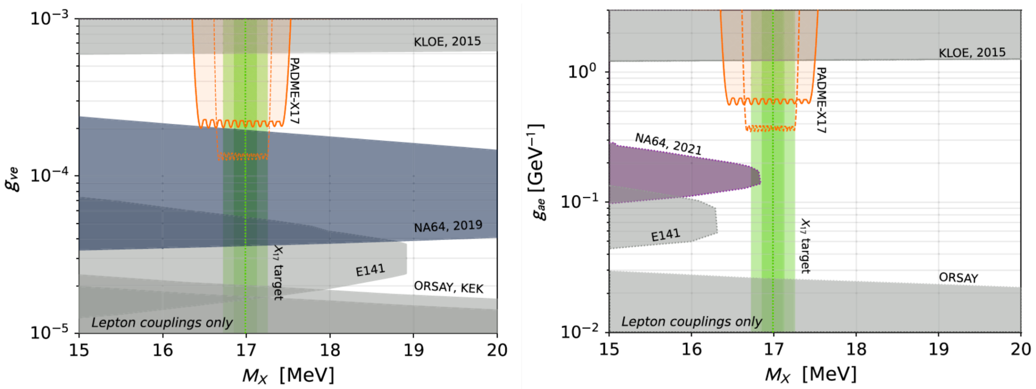

Figure 2: The expected PADME sensitivity in Run III. On the left is presented a X17 being a vector boson, while on the right is given an ALP X17 interpretation. [11]

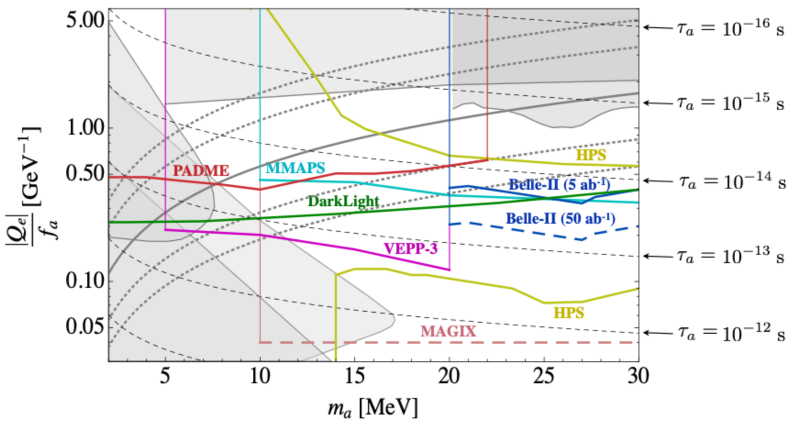

Figure 3: PADME sensitivity to ALPs.

particle. A modification to the PADME setup was done in the summer 2022. The dipole magnet was switched off and a new detector, ETag, based on plastic scintillators, was placed in front of the ECal. The signals from ETag will be combined with the information from the ECAL to precisely detect the e^+e^- pairs. A dedicated data taking was performed in autumn 2022, with analysis currently ongoing.

3.3 Prospects

The QCD axion, providing a solution to the strong CP-violation problem, is of interest for the particle physicists in the last half century. A more generalised version of the axions are the light pseudo-scalar axion like particles, ALPs. Their independent mass and coupling constant make the parameter space for research even wider than for the case of QCD axions. Although being originally designed to search for A', an ALP with mass in the interval 2 - 23.7 MeV/c^2 is also an attractive candidate for PADME [12].

The technique to search for ALPs could be quite similar to the one for A' [13], with PADME sensitivity region given in Figure 3. The visible decay modes are ALP$\rightarrow \gamma\gamma$ or a ALP$\rightarrow e^+e^-$ and are possible for detection in PADME.

The preliminary estimations showed that with the PADME setup from Run I and Run II and with the collected ~ 10^{13} positrons on target, the expected number of produced ALPs with mass M_{ALP} = 20 MeV and coupling constant g_{aee} = 1 is ~ 1000 events [14].

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