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Searching for the X17 with the PADME experiment

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The PADME experiment was originally designed to test dark matter theories predicting the existence of a "Dark Sector" composed of particles that interact with Standard Model ones exclusively through the exchange of a new, massive mediator. The confirmation of the X17 anomaly, observed in nuclear decays at the ATOMKI in Debrecen, sparked considerable interest in the particle physics community. If the anomaly arises from the decay of a new state into an e^+e^- pair, the time-reversal symmetry implies that it must be also producible through e^+e^- annihilation. The PADME experiment can rely on the world's only e^+ beam with the appropriate energy for a resonant production of X17. The collaboration dedicated 2022 data taking to investigate the X17 anomaly via $e^+e^- \rightarrow X17 \rightarrow e^+e^-$ reaction, aiming to probe the particle hypothesis. An overview of the scientific program of the experiment and the present status of the search for X17 at PADME are presented.

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1. Introduction

Despite the great success of the Standard Model (SM) of particle physics several major astrophysics observational phenomena still miss a consistent explanation, most notably, the origin of the matter-antimatter asymmetry in the Universe and the nature of Dark matter. In addition, there are a few smoking guns among the particle physics experimental results still in tension with the present understanding. This includes the long time existing discrepancy in the anomalous magnetic moment a_μ of the muon [1] and the observation of a structure in the angular distribution of e^+e^-, emitted through internal pair creation (IPC) in excited ^{8}Be, ^{4}He and ^{12}C nuclei [2–4].

All mentioned observations may have their solution in various extensions of SM, which predict the existence a new hidden sector of particles accessible only through a portal. In the simplest case the portal could be due to a new U(1) gauge symmetry, with a vector mediator [5]. Then the interaction of the new vector particle with the SM fermions is generally governed by a g_{vf} coupling, which may also arise effectively through mixing with the ordinary photon. In the case of IPC in ^{8}Be, ^{4}He and ^{12}C, the preferred mass of the hypothetical intermediate state particle, the X17, is M_{X17} = 16.85MeV [6], a value which could also be consistent with the measured a_μ [1].

2. The PADME experiment at LNF-INFN

The Positron Annihilation into Dark Matter Experiment (PADME) [7] aims to search for new light states with mass below O(20) MeV in positron-on-target annihilation process. PADME is located at Laboratori Nazionali di Frascati and utilizes positron beam with energy up to 490 MeV E_{beam} from the DAΦNE Linear accelerator, as shown in fig. 1. The accelerated positrons are deflected by a pulsed dipole magnet to a dedicated experimental hall, BTFEH1, where they are directed towards the PADME setup by an additional dipole magnet. The positron energy can be varied from O(100) MeV to about 500 MeV, when positrons are produced by a secondary target at the exit of the accelerator chain, or to about 430 MeV when a positron converter located after the first electron accelerator stage is used. The Linac provides 50 bunches of particles per second, one of which is deflected towards a spectrometer for energy monitoring and 49 are delivered to users.

The positron beam impinges onto a 100 μm thick diamond target with size 2 cm × 2 cm [8]. The ionisation charge in the diamond is readout by engraved by excimer laser horizontal and vertical strips. An evacuated region placed inside a 0.5 T dipole magnet follows. The vacuum tank hosts three sets of charged particle detectors, positron veto (PVeto), electron veto (EVeto) and the high energy positron veto (HEPVeto) made of plastic scintillator bars and readout by Hamamatsu S13360 silicon photomultipliers, which allow the detection of lower energy positrons due to hard bremsstrahlung emission in the target [9]. The neutral products of the interaction of the positrons in the target are detected by a ring-shaped segmented electromagnetic calorimeter (ECal, [10]) made of 616 BGO crystals, read out by HZC 1911 photomultipliers. The inner hole of the ECal is covered by a Cherenkov calorimeter composed by 5 × 5 matrix of PbF_2 crystals, the SAC (Small Angle Calorimeter) [11], which allows to disentangle the high rate of bremsstrahlung photons with $E_\gamma \geq 50$MeV.

PADME started taking data in the autumn, 2018 with secondary positron beam with multiplicity of 20000 positrons per bunch and energy $E_{beam} \simeq 490$ MeV for an e^+e^- invariant mass $M_{e^+e^-}$ =

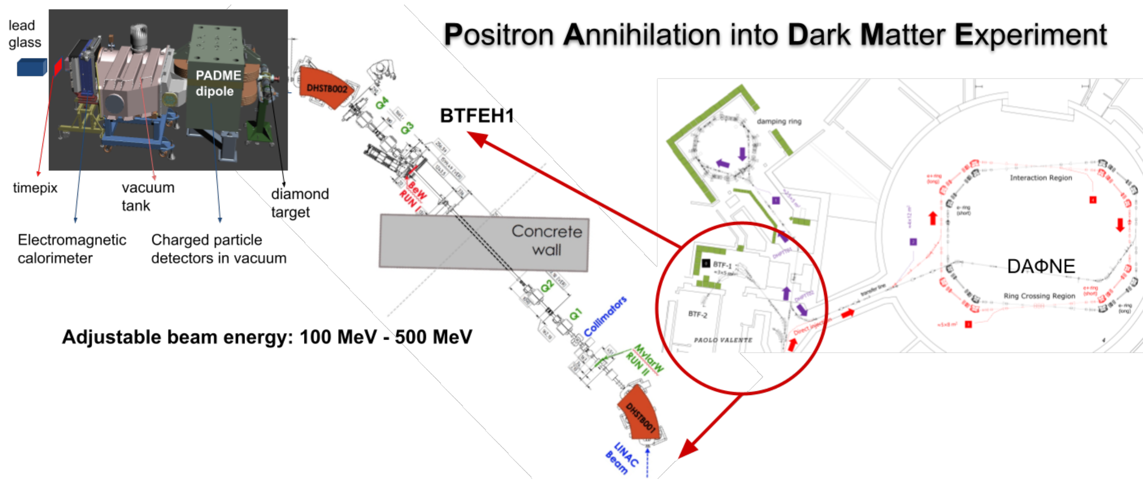

Figure 1: A sketch of the PADME experiment together with the DAΦNE accelerator complex. The DHSTB001 dipole magnet deflects the positrons to BTFEH1 while DHSTB002 directs them towards the PADME target.

22.4 MeV. The recorded data, so-called RUN I, was extensively used for detector calibration and commissioning of the experimental setup and for understanding and developing methodology for background suppression.

In the autumn, 2020 a three month long data taking period was initiated, the so-called RUN II, with primary positron beam with energy $E_{beam} \simeq 430$ MeV and an upstream Mylar window instead of a beryllium one to protect the Linac vacuum. Although with lower beam energy leading to a reduced invariant mass ($M_{e^+e^-} = 21$ MeV) and thus slightly reduced access to the new light particles parameter space, the primary positron beam exhibited much smaller beam induced background. Both RUN I and RUN II were devoted to the search for associate production of new states A' in the process $e^+ + e^- \longrightarrow A' + \gamma$. Upon the detection of the recoil photon, the missing mass squared, $M^2_{miss} = (P_{e^+} + P_{e^-} - P_\gamma)^2$ is used as a signal discriminator, where P_{e^+}, $P_{e^-} = (m_e, 0, 0, 0)$, P_γ are the positron, electron and the measured gamma four-momenta, respectively.

RUN III took place in autumn, 2022 with a modified experimental setup, dedicated to the search for X17 in the so called resonant production mode [13]. Due to the expected enhanced X17 production cross-section at resonant beam energy, the beam intensity was limited to ≤ 3000 positrons per bunch, decreasing significantly the beam induced background. The dipole magnet together with EVeto, PVeto and HEPVeto were switched off, a new charged particle detector (ETagger) made of plastic scintillators and readout by SiPMs was placed in front of the ECal, SAC was removed and a matrix of 2×6 Timepix3 silicon pixel detector array [12] was placed downstream of the ECal to measure the beam size and position at the exit of the experimental setup. In addition, a lead glass block placed after the Timepix3 served as a beam dump and measured the beam multiplicity by measuring the total deposited energy for each bunch [14].

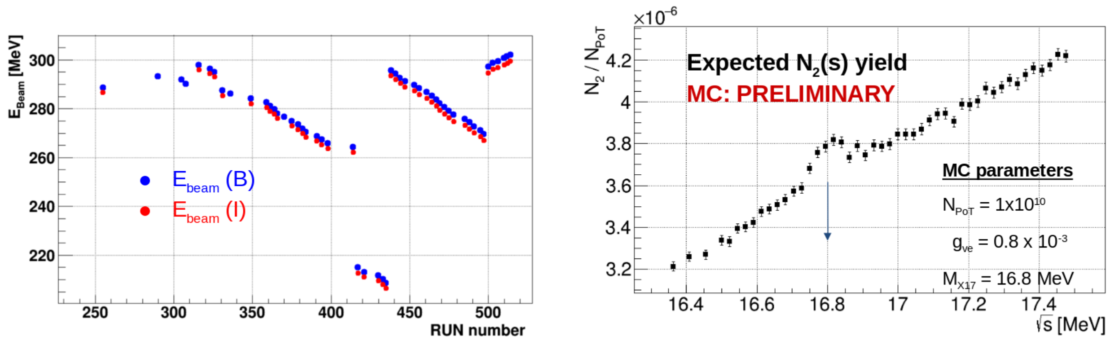

Figure 2: Left: A summary of the PADME runs taken at different beam energy, measured by monitoring the dipole magnet current and by Hall probes. Right: Expected rate of the reconstructed two cluster events in the case of a presence of a new state with mass $M_{X_{17}} = 16.8$ MeV with coupling $g_{ve} = 0.8 \times 10^{-3}$.

3. Searching for new light particles

PADME executed two separate search campaigns for new light particles exploiting the missing mass technique (RUN I and RUN II) by reconstructing single photon final states, and the resonant X17 production technique. While the analysis of the single photon events in RUN I and RUN II is still in progress and profits from the development of new methods for the mitigation of higher ECal occupancy [16], the analysis of a fraction of the PADME data of events with two clusters in the ECal lead to the most precise measurement of the semi-inclusive cross-section for the process $e^+e^- \to \gamma\gamma$ [15] at $E_{beam} = 430$ MeV:

$$\sigma(e^+ + e^- \to \gamma\gamma) = (1.977 \pm 0.018_{stat} \pm 0.119_{syst}) \text{ mb}. \tag{1}$$

To probe the X17 existence, PADME performed a scan on the e^+e^- invariant mass profiting from the significant increase of the X17 production cross-section when $M_{e^+e^-} \sim M_{X_{17}}$ [17] and the possibility to vary the DAΦNE Linac beam energy. Thus the contribution of X17 is seen as a change in the $\sigma(e^+ + e^- \to e^+ + e^-)$ cross-section as a function of $\sqrt{s}$.

An energy scan was performed, collecting data at 47 points with positron beam energy 263 MeV $\leq E_{beam} \leq$ 299 MeV, spaced by 0.7 MeV. This provided access to 16.4 MeV $\leq M_{X_{17}} \leq$ 17.5 MeV. In addition, several data samples with lower ($\sim$ 210 MeV) and higher (402 MeV) beam energy were recorded for calibration and systematic assessment purposes. The beam energy was monitored through the current of the DHSTB001 dipole and by a hall probe. The data samples (runs) with different positron beam energy are illustrated in fig. 2, left. For each energy point about 10^{10} positrons on target were collected.

With the PADME dipole magnet off during the entire RUN III, both $e^+ + e^- \to e^+ + e^-$ and $e^+ + e^- \to \gamma\gamma$ final states were detected as two cluster events by the ECal. Since $\sigma(e^+ + e^- \to e^+ + e^-) \gg \sigma(e^+ + e^- \to \gamma\gamma)$, the change in the total number of all two cluster events N_2 with the $\sqrt{s}$ was used to probe the existence of X17. For example, the number of the expected two cluster events as function of $\sqrt{s}$ for an X17 mass of 16.8 MeV and X17 coupling to electrons $g_{ve} = 0.8 \times 10^{-3}$ is shown in fig. 2, right. The analysis strategy is to discriminate

$$N_2(s) = N_{PoT}(s) \times [B(s) + S(s; M_{X_{17}}, g_{ve})\varepsilon_S(s)] \quad \text{versus} \quad N_2(s) = N_{PoT}(s) \times B(s), \tag{2}$$

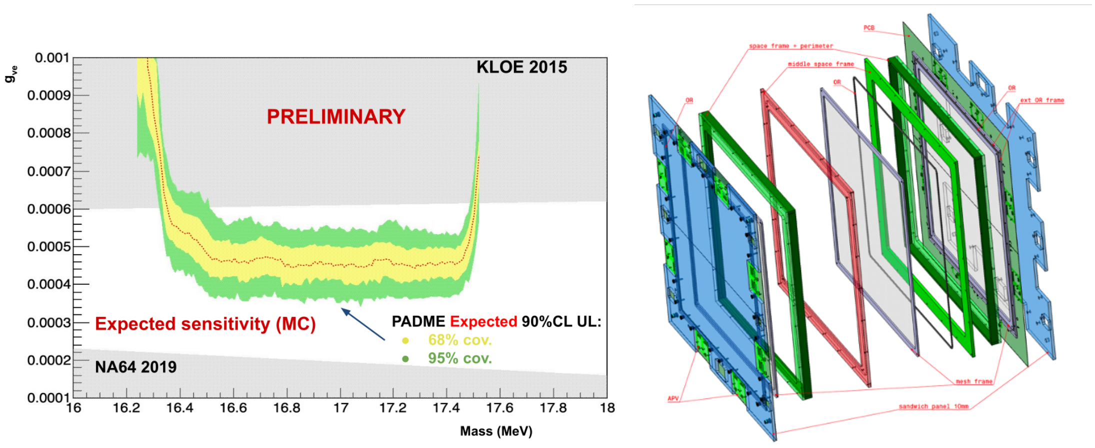

Figure 3: Left:Preliminary estimation of the PADME sensitivity (90% CL limits) to the X17 parameter space with RUN III data. Excluded regions by KLOE [18] and NA64 [19] are also presented. Right: A sketch of the new PADME Micromegas chamber to discriminate between charged and neutral 2 cluster final states and to provide measurement of the charged particle directions.

where $N_2(s)$ ($s = \sqrt{s}^2$) is the number of two cluster events, $B(s)$ is the background yield per positron on target, $N_{PoT}(s)$ is number of the positrons on target, $\varepsilon_S(s)$ is the signal selection efficiency, $S(s; M_{X_{17}}, g_{ve})$ is the signal production strength as function of the X17 mass, coupling and e^+e^- invariant mass, and $\sqrt{s}$ determined run by run from the measured beam energy. To decrease bias, $N_2(s)$ is kept blind throughout the analysis. All geometry cuts were performed with respect to the positron beam position at the ECal plane, determined by the center of gravity of two cluster events and validated by the Timepix3 data. The beam multiplicity for each energy point was measured by the lead glass block, calibrated extensively and taking into account the transversal energy leakage due to the change of the beam position and beam size at the Timepix3 run by run.

The expected PADME sensitivity with the described analysis technique applied to the RUN III data is shown in fig. 3, left. As can be seen, PADME will probe completely unexplored region with the already collected data.

The dominant limitations in the analysis of PADME RUN III data were identified to be the precise knowledge of the number of positrons on target and the two cluster events acceptance systematics. Both can be addressed by selecting a different normalization channel, $e^+e^- \to \gamma\gamma$, and measure the relative cross section $\sigma(e^+e^- \to e^+e^-)/\sigma(e^+e^- \to \gamma\gamma)$ as a function of $\sqrt{(s)}$. The similarity in the topology cancels to high extent the acceptance related effects and the relative ratio does not suffer from absolute beam flux determination. For precise charged particle identification and discrimination between e^+e^- and $\gamma\gamma$ final states, a new Micromegas based detector (fig. 3, right) with a central anode plane and two signal readout planes is foreseen to be placed in front of the ECal. The necessary 0.5 % uncertainty in the $e^+e^- \to \gamma\gamma$ sample will be achieved by collecting larger number of positrons-on-target per energy scan point. Preliminary estimations indicate that with the proposed upgrade and six months of data taking PADME will be able to probe the entire allowed X17 parameter space. A run with the described improvements was scheduled and will take place in 2025.

4. Conclusions

The PADME experiment at LNF-INFN is probing the existence of new states with mass below ~22 MeV in e^+ on target annihilation process, collecting more than 10^{13} positrons on target in three data taking campaigns. While RUN I and RUN II data exhibits higher occupancy in the electromagnetic calorimeter, the analysis of the data dedicated to the search for resonant production of X17 is at advanced stage and the expected sensitivity covers so far unexplored X17 parameter space. PADME foresees a new run in 2025 with an upgraded setup which will allow to completely probe the allowed parameter space for 16.4 MeV $\leq M_{X_{17}} \leq$ 17.4 MeV.

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