

Calibration of the PADME beam monitoring calorimeter

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A hypothesis for a new light particle of 17 MeV mass (X17) is currently being investigated at several nuclear and particle physics experiments, one of which is the Positron Annihilation into Dark Matter Experiment (PADME), based at Laboratori Nazionali di Frascati - INFN, Italy. To probe the existence of the X17 particle at PADME, a high-precision measurement of the beam characteristics is required. In 2024, a dedicated test run campaign was conducted to calibrate the beam monitoring calorimeter. Two main effects have been recognised as significant for the data analysis of PADME, namely a radiation-induced performance degradation and an energy loss in the passive material in front of the detector. In this paper, the main results from the 2024 test run are presented, and the luminosity corrections made in the PADME X17 analysis are discussed.

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1. X17 anomaly

Over the last ten years, the ATOMKI collaboration in Debrecen, Hungary, has been investigating the so-called X17 anomaly. Initially, a study of nuclear decay of the excited isotope ^8Be via internal pair creation (IPC) showed an excess in the distribution of the opening angle between the electron-positron pair at around 140° [1]. Similar effects have been observed in the decay of excited ^4He and ^{12}C nuclei [2, 3]. These results by ATOMKI are compatible with the production and successive decay of a short-lived particle with a mass of around 17 MeV, namely X17.

Several possible explanations for the nature of this new particle exist. The most preferable at the moment is the massive vector boson solution, which can be theoretically described by adding a new term in the Standard Model (SM) Lagrangian. The corresponding Lagrangian would be:

$$\mathcal{L} \propto \mathcal{L}_{SM} + \mathcal{L}_{X\psi} + \mathcal{L}_X^m = \mathcal{L}_{SM} + g_{v\psi} X_\mu(x) \bar{\psi}(x) \gamma^\mu \psi(x) + \frac{1}{2} m_X^2 X_\mu X^\mu, \quad (1)$$

where the new vector boson X with mass m_X interacts with the fermion field ψ with a coupling constant $g_{v\psi}$.

The hypothetical X17 boson gathered a lot of attention in the nuclear and particle physics community due to its possible relation to dark matter [4]. In the minimal scenario, X17 can be produced in e^+e^- interaction, and decay into an e^+e^- pair.

2. The PADME experiment

The Positron Annihilation into Dark Matter Experiment (PADME) is a fixed-target experiment, originally planned to search for the dark photon A' via its associated production in positron-on-target annihilation [5]. In 2022, PADME started a data-taking campaign for studying the production of the X17 boson in resonance annihilation, with a consequent decay into an electron-positron pair:

$$e^+ + e^- \rightarrow X17 \rightarrow e^+ + e^-$$

During PADME Run III a beam energy scan around the hypothetical X17 resonance energy was conducted, where $E_{beam} = [262; 296]$ MeV, corresponding to a centre-of-mass energy range for the e^+e^- pair of $\sqrt{s} = [16.4; 17.4]$ MeV. In the case of the existence of X17, it is expected to observe an increase in the number of e^+e^- pairs in the final state with respect to the SM processes around $M_X \sim 17$ MeV. The observable in the experiment is the number of two-particle final states normalised to the number of positrons-on-target (PoT): N_2/N_{PoT} . This implies that the number of PoT should be known with less than percent precision to obtain a result with an overall uncertainty of the order of 1%.

3. Test beam for characterisation of the PADME beam monitoring detectors

In PADME Run III, two main beam monitoring detectors were implemented: a Timepix3 array to monitor the beam spot position and size [6], and a lead-glass calorimeter to measure the beam multiplicity. The PADME beam catcher detector is a Cherenkov electromagnetic calorimeter, consisting of a lead-glass block Schott SF57 (75% PbO) with density of $\rho = 5.5 \text{ g/cm}^3$, a photomultiplier (PMT) Hamamatsu R2238 and a multichannel ADC CAEN V1742.

A dedicated test run was performed in 2024 to study and cross-calibrate the response of the Timepix3 and lead-glass detectors. In this test run, two types of effects were found to be relevant to the consequent data analysis for PADME X17 Run: upstream energy-loss and radiation-induced performance degradation of the lead-glass calorimeter.

3.1 Position dependence of the charge measurement

Horizontal and vertical beam position scans were conducted during the test beam to study the response uniformity and energy leakage in the lead-glass detector. For this scan, a 285 MeV electron beam with a multiplicity of around 500 particles per spill, each with a length of roughly 10 ns, was used. The beam spot was measured at the Timepix3 plane to have an area of approximately $5 \times 5 \text{ mm}^2$ and was maintained stable throughout the entire test run. For each position scan point, the distribution of the reconstructed charge in the lead-glass is approximated by a Gaussian function to obtain the mean charge $Q(X, Y)$. The result from the position scan is shown in Figure 1.

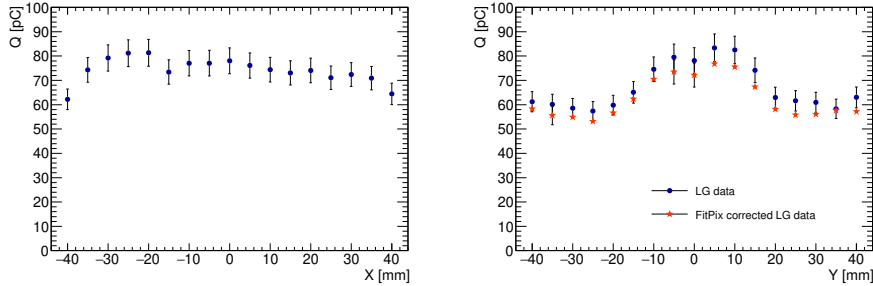


Figure 1: Reconstructed charge in the lead-glass calorimeter as a function of the beam X (left) and Y position (right). The charge in the Y scan was corrected for the beam multiplicity, which was measured from a silicon-pixel detector, the BTF FitPix (orange points).

The specific shape of the Y profile was found to be due to a variable amount of passive material before the lead-glass calorimeter. This was confirmed by comparing the data with a Monte Carlo simulation, after including a detailed description of the involved detectors, as shown in [7]. The beam particles with $|Y| < 14 \text{ mm}$ are passing through the Timepix3 sensors and lose a minimal amount of energy, while particles with $14 \text{ mm} < |Y| < 40 \text{ mm}$ transverse the copper frame of the Timepix3 cooling system and lose more than 10% of their energy.

The position-dependent energy loss was identified and properly accounted for in the data analysis of PADME Run III, where the beam spot movements for each energy point induce a sizable effect in the lead-glass response.

3.2 Lead-glass response calibration

For the absolute luminosity calibration method of the lead-glass calorimeter, a scan was conducted using a 450 MeV electron beam with an average multiplicity of 3 particles per spill, while varying the high voltage (HV) on the PMT. The spectrum of the reconstructed charge Q for 1000 V is shown in Figure 2 (left). The six distinguishable peaks correspond to the different numbers of beam particles that deposited their energy in the lead-glass block, and the distribution

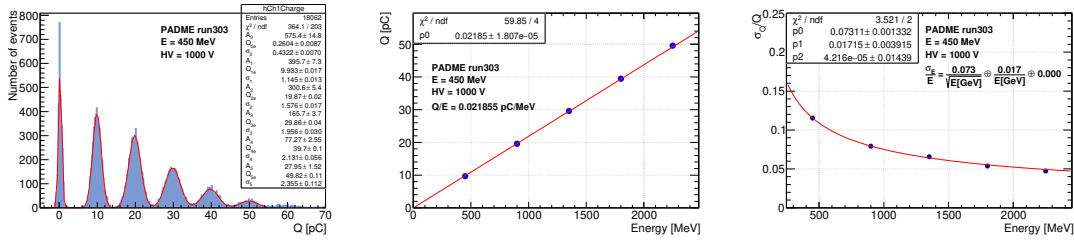


Figure 2: Reconstructed charge spectrum for 1000 V (left). Mean reconstructed charge as a function of the particle energy $E = N.E_{beam}$ (center). Relative standard deviation of the reconstructed charge as a function of the particle energy E (right).

is fitted with a sum of six independent Gaussian functions. The peak at 0 accounts for the pedestal, and its mean value is subtracted from the rest of the mean charge values.

The mean values $Q(E, HV)$ and the relative standard deviation σ_Q/Q of the reconstructed charge for each peak are shown in Figure 2 (center, right) as a function of the impinging energy, taken as $E = N.E_{beam}$, where N is the number of beam particles. The mean charge plot is approximated with a linear function $Q = p_0.E$, where the slope gives the value of the charge in pC deposited in the calorimeter per 1 MeV energy for the given HV. The same procedure is repeated for several HV values, and the parameter $p_0 = Q/E$ [pC/MeV] is plotted as a function of the voltage in Figure 3. The data points are fitted with the relation: $Q/E = A.HV^B$. By extrapolating this function down to 650 V, the calibration coefficient for the nominal working condition of the calorimeter during Run III is determined, and it is found to be $Q/E = 0.8231 \pm 0.0006$ fC/MeV. This value is, in principle, independent of the beam energy.

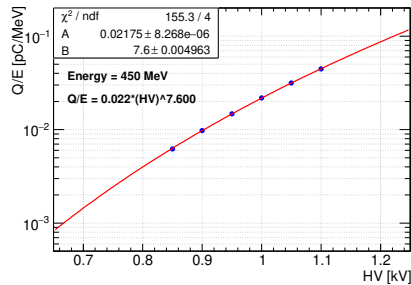


Figure 3: Relation between the reconstructed charge per MeV and the high voltage at 450 MeV beam energy.

The latter result is not consistent with the value from previous test runs, preceding the 2022 data taking for calibration of this detector [8]. This is because the transparency of the SF57 lead-glass block has been affected by the accumulated dose. Throughout Run III, a total of 7.10^{11} PoT (of ~ 300 MeV each) have been absorbed in the lead-glass block corresponding to a total dose of about 25 Gy (or 2.5 krad). To our knowledge, the SF57 radiation-induced transmittance loss has not been measured in the literature. Information about similar blocks (SF5-SF6) is available, where a significant dose-dependent effect in the lead-glass transparency for photons with Cherenkov wavelengths is visible [9]. Consequently, the radiation-induced loss in Run III was quantified by using the cumulative energy in the PADME ECal and the integrated positron flux determined from the Target, and the lead-glass reconstructed charge was corrected for the absorbed dose [7].

4. Conclusions

The PADME experiment requires a precision of less than 1% in the beam characteristics to probe the existence of the X17 boson. Data from 2024 test run with the Cherenkov lead-glass calorimeter were analysed to study the calibration coefficient for the accurate determination of the beam luminosity. Two main effects have been recognised and quantified for X17 data analysis: the energy loss in the upstream passive material, and the radiation-induced transparency loss, leading to a total uncorrelated systematic uncertainty of 0.35%. The PADME Run IV employed an LED pulser and a second lead-glass block as a reference for the light yield response of the beam monitoring calorimeter to further reduce the systematic uncertainty in the measurement below 0.3%.

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