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Investigating the dark sector with the PADME experiment

P. Gianotti for the PADME Collaboration(*)
INFN, Laboratori Nazionali di Frascati - Frascati, Italy

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Summary. — In the attempt of justifying some unexplained physics phenomena like dark matter nature or the $(g-2)_\mu$ anomaly, the existence of new light particles with a wide range of properties has been postulated by several theoretical extensions of the Standard Model. Among the others, a light particle of mass ∼17 MeV (named X17) decaying in e^+e^- has been put forward to explain an anomaly observed since 2016 in a series of nuclear physics studies performed by the ATOMKI group of Debrecen in Hungary. If confirmed, this new state will represent a real breakthrough in the search of physics phenomena beyond the Standard Model. The PADME experiment at the Laboratori Nazionali di Frascati of INFN, searching for a dark photon and/or other dark sector candidates among the annihilation products of a beam of positrons on the electrons of a fixed target, has the unique opportunity to confirm/disprove the particle nature of such an anomaly. In the second half of 2022, the collaboration performed a data taking campaign centered at $\sqrt{s}$ ∼17 MeV in order to produce on-shell the X17. The collected data are under analysis and this paper presents an overview of the PADME results and perspectives.

1. – Introduction

The nuclear physics group of the ATOMKI institute of Debrecen in Hungary, while studying the de-excitation of several highly energetic states of ^{8}Be, ^{4}He and ^{12}C nuclei via Internal Pair Creation (IPC), observed an anomaly in the opening angle and invariant mass distributions of the final state e^+e^- pairs [1-3]. A possible explanation of this effect is the creation and subsequent decay of a particle of mass approximately 17 MeV which has been named X17. Within the particle physics community a wide debate is

(*) S. Bertelli, F. Bossi, R. De Sangro, C. Di Giulio, E. Di Meco, D. Domenici, G. Finocchiaro, L. G. Foggetta, M. Garattini, P. Gianotti, M. Mancini, I. Sarra, T. Spadaro, E. Spiriti, C. Taruggi, E. Vilucchi, V. Kozhuharov, K. Dimitrova, G. Georgiev, S. Ivanov, Sv. Ivanov, R. Simeonov, F. Ferrarotto, E. Leonardi, E. Long, G. C. Organtini, G. Piperno, M. Raggi, P. Valente, A. Variola, A. Frankenthal, I. Oceano, F. Oliva.

ongoing. Many theoretical interpretation of the X17 in terms of a new scalar or vector state have been put forward, and possibly unaccounted Standard Model (SM) effects have been investigated [4, 5]. On the experimental side, searches have been proposed and/or are taking data with the goal of independently investigate this anomaly. Among the others, the Positron Annihilation into Dark Matter Experiment (PADME) ongoing at the Frascati National Laboratory (LNF) of the Italian Institute for Nuclear Physics (INFN). In the following sections the experimental setup and the scientific program of this initiative are described.

2. – The PADME experiment

The scientific program of PADME regards the study of dark matter at accelerators. The main goal of the experiment is to search for a dark photons A' produced in the annihilation of a positron beam with the electrons of a 100 μm thick active diamond target [6]. The reaction under study is $e^+e^- \rightarrow A'\gamma$, with the A' undetected. Therefore, events with a single photon and nothing else in the setup (see fig. 1) have to be selected. Knowing the energy of the incoming positron and measuring the recoil photon 4-momentum, the missing mass can be computed. In case an A' is produced, a pick at its mass value will appear above the SM background.

Actually, the PADME approach can be sensitive to several other dark matter candidates like axion-like particles, dark Higgs and eventually the X17 that can be produced resonantly and then detected via its decay in a e^+e^- pair [7].

The PADME detector is sketched in fig. 1. The setup has to detect the products of the interaction of the positron beam with the active diamond target able to count the incoming positrons and to reconstruct their interaction point with a precision below 1 mm both in x and y directions. The charged particles are detected and vetoed by 3 modules of scintillator sticks. Two of them are installed in vacuum along the opposite sides of a dipole magnet that has the double function of deflecting toward the beam dump the positrons that have not interacted, and to allow the determination of e^+ and e^- momenta. The third one is located out of the main vacuum chamber to detect highest-energy positrons. Photons are detected by means of a calorimetric system. This last one

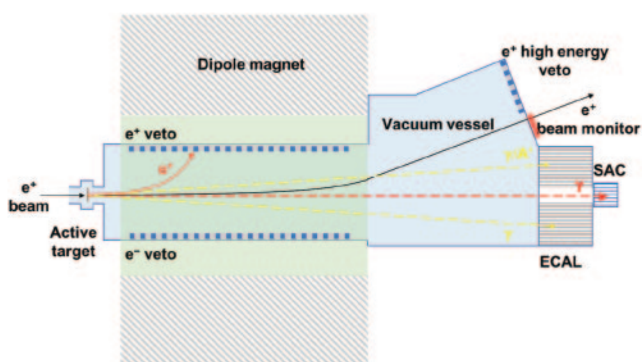

Fig. 1. – Layout of the PADME setup. The main detector components are schematically shown (see text for details). In the picture the possible trajectories are also drawn for a $\gamma\gamma/\gamma A'$ event (in yellow), for a Bremsstrahlung event (in red), and the path for not interacting positrons (in black).

is composed by two modules: ECAL, a cylindrical array of 616 BGO crystals (energy resolution better than 3%) arranged with a central hole and a small angle PbF_2 array (SAC) placed exactly behind ECAL hole. This arrangement is necessary to avoid that Bremsstrahlung photons, which are copiously emitted in the forward direction, would blind the main calorimeter whose response time is not fast enough to stand their rate ($\sim$40 MHz). On the contrary, the 25 PbF_2 crystals, readout by fast PMTs, are perfectly suited to veto these photons in combination with the e^+ veto. The setup is completed by a solid state pixel detector, placed on the beam exit to further improve the experiment beam monitor capability.

The PADME Collaboration had two data taking periods in winter 2019 and 2020 (Run I and Run II) during which similar statistics were collected ($\sim 5 \times 10^{12}$ Positron on Target, PoT) at 490 and 430 MeV beam energies, respectively. In between these two data collections, major improvements on the beam quality and its transport line were realized to reduce the background the beam induces in the apparatus [8]. Figure 2 (left) shows the energy of two photons final states measured by ECAL in 3 different run conditions (details are in the figure caption). The reduction of the background from Run I to Run II is evident.

A subset of Run II data were used to perform the most precise measurement of the cross-section $\sigma(e^+e^- \to \gamma\gamma(\gamma))$ below 1 GeV to date (see fig. 2 (right)). This measurement represents an important milestone for the collaboration for several reasons: first, this cross-section is linearly correlated to the cross-section of associate production of a dark photon and therefore it is the natural step to define a solid ground for the single photon analysis; second, this is the first measurement at beam energies below 500 MeV with precision better than 20%, and the only one in this energy range detecting the two final state photons. Thanks to this last point, the measurement can be used to fix limits for new physics contributions to SM.

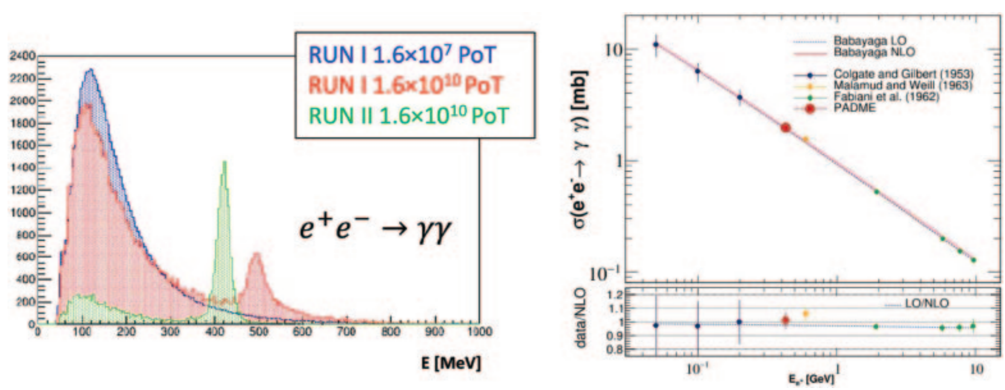

Fig. 2. – Left: sum of energies of photon pairs in PADME ECAL in three beamline configurations between Run I and Run II: i) blue, secondary beam; energy 545 MeV; intensity 25 k positrons/bunch; bunch length 250 ns; ii) red, primary beam; energy 490 MeV; intensity 25 k positrons/bunch; bunch length 250 ns; iii) green, primary beam; energy 430 MeV; intensity 28 k positrons/bunch; bunch length 280 ns. Right: theoretical predictions, at the leading order and next-to-leading order approximation for the cross-section $\sigma(e^+e^- \to \gamma\gamma)$ as a function of the positron energy. The PADME measurement is superimposed along with earlier measurements. Data to theory ratios are shown in the bottom pad [9].

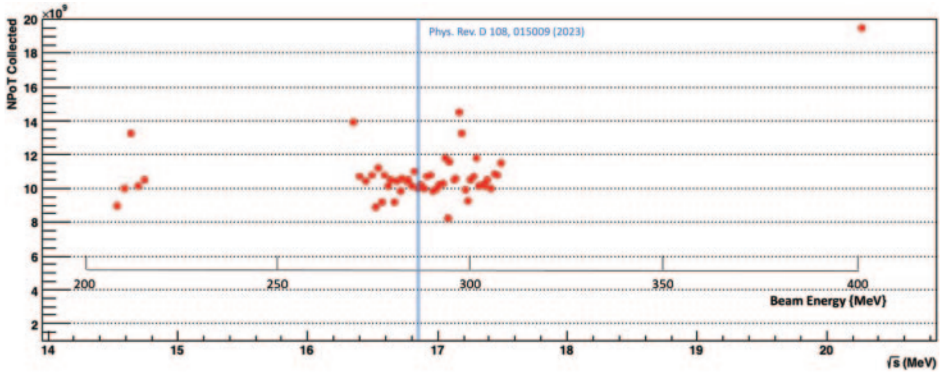

Fig. 3. – Number of positrons on target collected by PADME in Run III as a function of the center of mass energy (positron beam momentum is also indicated). The vertical light-blue line indicates the best fit to the mass of X17 performed using all the ATOMKI data (from ref. [10]).

3. – Resonant production of X17

As mentioned in the introduction, if the "ATOMKI anomaly" is due to a new particle, PADME is in the ideal position to contribute to understanding its nature. In fact, LNF is the only laboratory in the world owning a positron beam that can be tuned to produce resonantly the X17. The experimental technique, extensively described in ref. [7], consists in studying the process $e^+e^- \to X17 \to e^+e^-$ varying the beam energy in the interval 265–297 MeV, corresponding to a scan in the c.m. energy range 16.46–17.42 MeV. The X17 signal should appear as a bump above the SM background in the distribution of the measured number of e^+e^- pairs.

In the second half of 2022, the PADME Collaboration performed a data taking (Run III) to conduct the above mentioned set of measurements. For each of the 47 different energy values, 10^{10} PoT were collected, 5 of them below the resonance value and 1 above, as shown in fig. 3. The off-resonance points serve to validate the analysis strategy

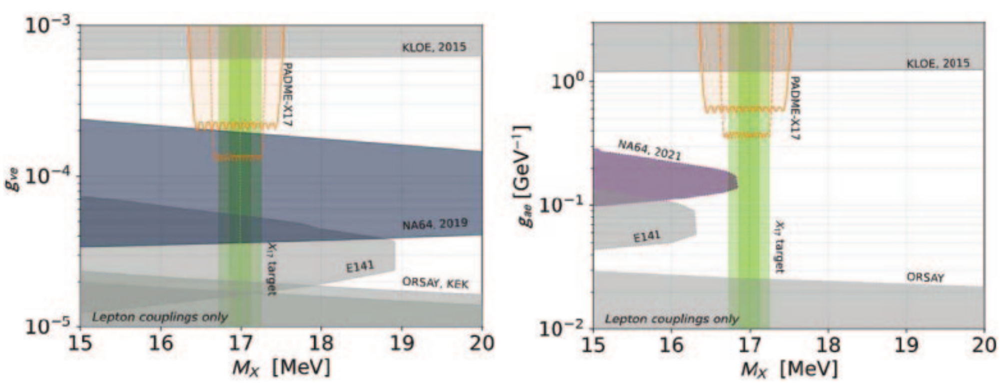

Fig. 4. – Expected sensitivities of PADME Run III on the coupling of a X17 vector boson (left) and pseudo-scalar (right) for 2 different values of beam energy spread (orange lines). The green bands represent the 1σ (2σ) X17 mass value obtained from a naive combination of the ^{4}He and ^{8}Be ATOMKI results. Regions already excluded by other experiments are also shown (from ref. [7]).

before unblinding the signal region. Figure 4 shows the projected 90% C.L. sensitivity of PADME on the g_{ve} coupling of the X17 for the two possible hypotheses on the quantum numbers [7]. The orange lines refer to an expected beam energy spread of 0.25% (solid) and 0.5% (dashed). The preliminary ongoing analysis points toward the direction of an effective value of $\sim 0.3\%$. Therefore, the expected sensitivity of PADME Run III will lay in between the two curves.

4. – Conclusions

The PADME experiment is sensitive to any new particle produced in e^+e^- collisions in the tens of MeV energy scale: dark photons, low mass dark Higgs, leptonic gauge bosons. This peculiarity turned out to be ideal to investigate the particle interpretation (X17) put forward to explain the nature of an anomaly observed in the study of several nuclei excited states. A dedicated data taking to produce resonantly the X17 has been conducted in the second half of 2022 and currently the data analysis is ongoing.

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