Bulgarian Journal of Physics vol. **47** (2021) 62–69

The PADME Experiment and Dark Matter Searches

R. Simeonov[1]

Faculty of Physics, University of Sofia "St. Kl. Ohridski",
5 James Bourchier Boulevard, BG-1164 Sofia, Bulgaria

Received *9 December 2020*

Abstract. The modern world of physics still has many unanswered questions on the road of creating a theory, which describes the Universe on fundamental level. The Standard Model of particle physics seems unable to explain the nature of phenomenons like the Dark Matter. The PADME experiment aims to study one possible candidate addressing the nature of Dark matter - a hypothetical vector boson massive particle called Dark Photon A'. This particle could be created through the reaction $e^+ + e^- \rightarrow \gamma + A'$ and observed indirectly via a missing mass technique. PADME experiment is finalizing it's second data acquisition run and should provide new information for the dark photon in the mass region $2 - 23.7$ MeV.

KEY WORDS: Dark Matter, Dark Photon, Dark Sector, Design of Experiment

1 Introduction: The Incompleteness of the Standard Model

The classification of all known elementary particles and their interactions are summarized in the so called Standard Model (SM). The development of this model is one of the greatest achievements of the 20th century. The discovery of the Higgs Boson in 2012 was thought to give the last unknown answers and to provide the final chapter of a theory, describing the world around us on a fundamental level. Unfortunately, the value of the mass of the Higgs boson, measured to be ≈ 125.18 GeV tend to be not enough for this role [1]. There are still hidden parts of the puzzle, such as the neutrino masses, the explanation of the Baryogenesis, the undetected yet CP-violation in the strong interactions.

[1]For the PADME collaboration: A.P. Caricato, M. Martino, I. Oceano, F. Oliva, S. Spagnolo (INFN Lecce and Salento Univ.), G. Chiodini (INFNLecce), F. Bossi, B. Buonomo, R. De Sangro, D. Domenici, G. Finocchiaro, L.G. Foggetta, M. Garattini, A. Ghigo, F. Giacchino, P. Gianotti, I. Sarra, B. Sciascia, T. Spadaro, E. Spiriti, C. Taruggi, E. Vilucchi (INFN Frascati), V. Kozhuharov (Sofia Univ. and INFN Frascati), G. Georgiev, S. Ivanov, R. Simeonov (Sofia Univ.), F. Ferrarotto, E. Leonardi, F. Safai Tehrani,P. Valente (INFN Roma1), S. Fiore (ENEA Frascati and INFN Roma1), E. Long, G.C. Organtini, G. Piperno, M. Raggi (INFN Roma1 and Sapienza Univ.), B. Liberti (Tor Vergata Univ. and INFN Frascati), M. Martini (Marconi Univ. and INFN Frascati), J. Alexander and A. Frankental (Cornell Univ.)

2 Dark Matter

The first evidence of the existence of Dark Matter (DM) was found by Fritz Zwicky. He used the virial theorem to calculate the gravitational mass of the galaxies inside the Coma cluster. The values obtained were 400 times greater than the expectations based on the luminosity of the same galaxies. He showed that this could only be possible if there was unseen dark matter, “dunkle (kalt) Materie” [2], which was holding them by gravitation.

After Zwicky’s research, Vera Rubin was the next astronomer who contributed for the development of DM studies. [3] The question standing out today is what DM is made of. The biggest challenge to detect DM is that, unlike ordinary matter, the DM does not interact through the Electromagnetic force. We can judge for its presence only by its gravitational effects on ordinary matter. None of the particles of the SM is a good candidate to explain the whole DM in the Universe. A theory [4] suggests that there exists a whole new hidden sector of particles, different from those of the SM, which may interact with still unknown forces. Those particles should be the constituents of the DM and they interact with the SM particles via the so called “portals”. In the simplest model, a new U(1) gauge symmetry group with carrier acting as a portal between the Standard Model and the hidden sector is employed. This portal is a massive vector boson particle named Dark Photon (A'). A' should mix with the SM photon and couple with the SM particles with a constant ϵ. Only two new parameters are needed to describe this new particle – its mass and ϵ.

3 The PADME Experiment

PADME (Positron Annihilation into Dark Matter Experiment) [5] is located at the Beam Test Facility of the Laboratori Nazionali di Frascati (LNF) in Italy. It is a small scale fixed target experiment and it is set to look for dark photons via the reaction $e^+ + e^- \to \gamma + A'$. The mass of the dark photon is determined using the missing mass technique, which requires the knowledge of the initial parameters of the e^+ beam, the e^- target at rest and the energy-momentum of the final state γ. The missing mass squared is given by

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

where $P_{e^+_{\text{beam}}}$, P_{e^-}, P_γ are the 4-momentum of the positron, of the electron and of the emitted γ respectively. The A' will appear as a peak at a fixed position in the missing mass distribution.

The only assumption of the proposed experimental technique is that the dark photon couples to leptons.

3.1 PADME physics case

The experiment uses a positron beam provided by the DAΦNE LINAC. The beam can reach energy of 550 MeV and it is produced in bunches at frequency of 50 Hz. Each bunch contains about 2×10^5 e^+ particles and has a duration of $\sim$ 200 ns. The beam used in the March 2020 data acquisition run was with energy of 490 MeV, while the one used in the September–November 2020 run was with energy of 430 MeV and beamlength $\sim$ 300 ns [6]. The energy of the beam, due to kinematical considerations, gives access to masses for the dark photon in the range of 2–23.5 MeV.

A dark photon with mass in the given range may also explain at least partially the discrepancy between the expected and the measured value of the muon anomalous magnetic moment $(g-2)_\mu$. The experiment is also sensitive to Axion-Like Particle studies. Another possible research to be made on PADME is the Beryllium-8 anomaly. [9]

The previously excluded areas for the corresponding ϵ^2 and A' mass are shown in gray in Figure 1. However, some of the exclusions are highly model dependent and assume dark photon interactions with both quarks and leptons, interaction constant unification, and others.

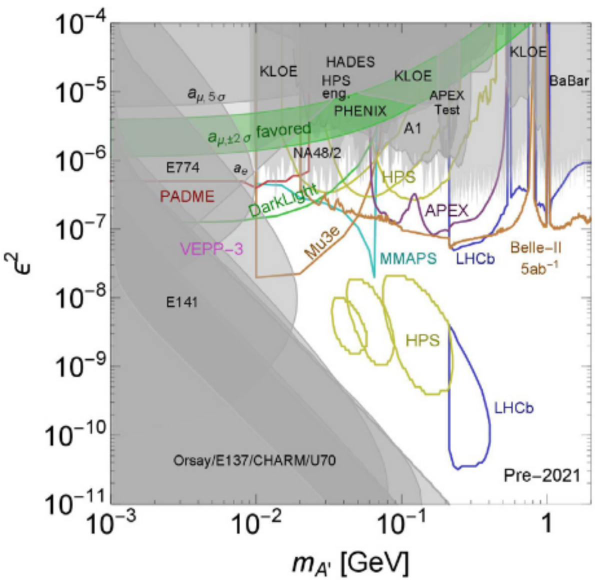

Figure 1. Projected sensitivity of the PADME experiment to the Dark photon parameter space $(M_{A'}, \epsilon^2)$ [7, 8].

3.2 Detector system

A schematics of the PADME experimental technique with the detector system is shown on Figure 2.

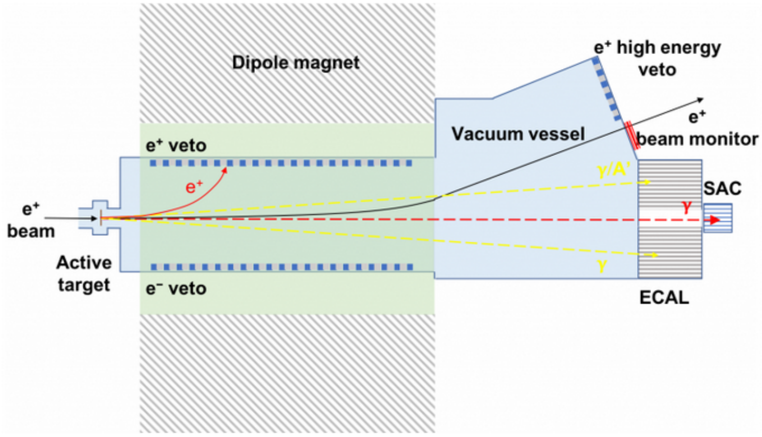

Figure 2. Scheme of the PADME Detector System.

The beam impinges on an active diamond target which leads to an annihilation process between the e^+ and the e^-. After this process, the Dark Photon, if produced, leaves the experiment undetected, while the recoil γ is measured by an Electromagnetic Calorimeter. The events with charged particles which had not taken part in the annihilation reaction, are suppressed thanks to 3 Veto Detectors - Electron Veto, Positron Veto and High Energy Positrons Veto. The charged particles which had lost most of their energy due to Bremsstrahlung, are bent by a magnetic field towards the veto detectors. A detailed Monte-Carlo (MC) simulation based on the GEANT4 software package is used to determine the sensitivity of the experiment.

3.2.1 Target

The target of the experiment is an active diamond target made by a polycrystalline diamond film. With thickness of 100 μm and surface of 400 mm^2, this element provides information about the beam position (resolution $\approx$ 5 mm) and multiplicity. This happens thanks to 16 $\times$ 16 graphitic strips engraved on the target surface via a laser technique. The low Z of the carbon and the thickness of the target are chosen to minimize the multiple scattering and background from Bremsstrahlung [10].

3.2.2 MIMOSA

A MIMOSA-28 detector gives information about the beam parameters before it enters the main part of the experiment. It consists of 2 monolithic sensors placed one after the other, each composed of a matrix of 928×960 pixels. This detector has the same dimensions as the diamond target and it monitors the position and divergence of the beam before the start of the data acquisition. Both the MIMOSA and the target are mounted on moving rails and only one of these components can be operated at the same time.

3.2.3 TIMEPIX3

A TimePix3 silicon pixel detector is placed at the exit of the experiment vacuum chamber. It monitors the non-interacted positrons. The main benefit of this detector is the measured position, time and energy of every single particle in a bunch. The whole detector consists of 12 sensors (with a total of 786 by 432 pixels) covering an area of 8.4×2.8 cm^2, and so far it is the biggest area covered with TimePix3 and used for particle physics.

3.2.4 Veto detectors

There are three types of Veto Detectors in the PADME experiment – Positron (PVeto), Electron (EVeto) and High Energy Positrons (HEPVeto). Each of these detectors is made of polystyrene plastic scintillator bars connected to a 3×3 mm^2 Hamamatsu 13360 silicon-photo multiplier (SiPMs) with a pixel of $25\ \mu$m. Both EVeto and PVeto are placed in vacuum ($< 10^{-5}$ mbar) and magnetic field (≈ 0.45 T). The PVeto has 90 active scintillating bars, while the EVeto is working with 96 bars. Both of them detect particles with momentum less than 450 MeV. The HEPVeto is placed out of the dipole magnet close to the beam monitor. Its role is to detect positrons with momentum up to 500 MeV. During the preliminary tests of the PADME Veto system, time resolutions of $\sim$ 500ps were measured. [11, 12]

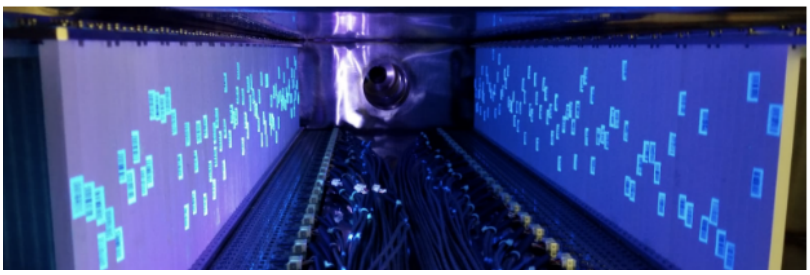

Figure 3. PADME veto detectors.

3.2.5 Calorimeter

The Electromagnetic Calorimeter (ECAL) of the experiment is placed at a distance of 3.46 m from the diamond target. It has a cylindrical-ring shape with an external radius ≈ 26 cm and it is made of 616 BGO crystals, each with size $2.1 \times 2.1 \times 23.0$ cm^3. The ECAL detects the γ in the final state. The distance from the target and the size of the detector provide angular coverage in the interval [15.7, 82.1] mrad. The scintilation light decay time of ~ 300 ns of the BGO crystals determines the necessity of another detector with much lower death time in order to be able to detect the higher rate of events due to the Bremsstrahlung radiation. That is why there is a hole at the center of the ECAL, behind which the Small Angle Calorimeter is positioned [13].

3.2.6 SAC

The Small Angle Calorimeter (SAC) is made of 25 lead difluoride (PbF_2) crystals with dimensions $3 \times 3 \times 14$ cm^3. As mentioned in the previous subsection, the role of this detector is to detect the photons emitted from the Bremsstrahlung and multiphoton events. SAC can distinguish two particles with time separation of ~ 3 ns and has angular coverage of [0, 20] mrad.

3.3 Background

The main background of the experiment is from annihilation $e^+e^- \rightarrow \gamma\gamma(\gamma)$ and Bremsstrahlung events $e^+N \rightarrow e^+N\gamma$. GEANT4 MC and data reconstruction allowed precise study of the beam-induced background observed during the first data acquisition run. This background originated from the beam interaction

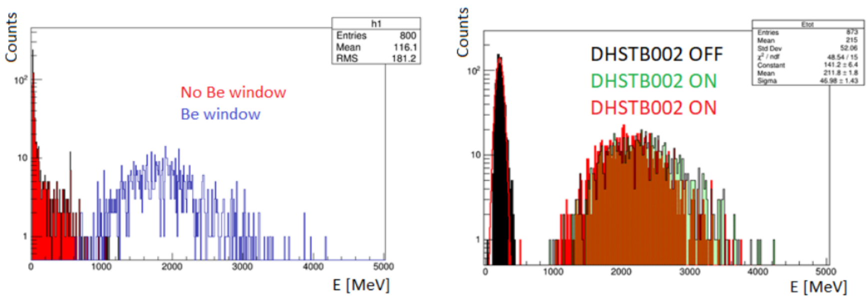

Figure 4. The total energy distribution in the ECal from the MC of the experiment, with and without the Beryllium window (on the left) compared to the total energy distribution of the collected data (on the right; DHSTB002 is the last dipole of the transfer line before the target) [14].

with the Beryllium window, which separated the accelerator vacuum from the detector vacuum. The interactions resulted in energy loss and beam particles scattering which afterwards hit the beamline and produced significant amount of Bremsstrahlung photons. A new mylar window was installed to decrease the expected background.

4 Conclusions

The nature of the Dark Matter still stays unsolved within the Standard Model. A completely new Dark Sector may shed light on the contemporary particle physics. The PADME experiment aims to observe a possible portal between both sectors - the so called Dark Photon. During PADME RUN-I all detectors of the experiment performed with the desired stability. The collected data helped in defining the background of the experiment, calibrating the detectors and improving the set-up. PADME RUN-II is currently ongoing and the collected data will be used for precise background estimation.

Acknowledgements

The work is partly supported by BG-NSF DN-08/14 from 14.12.2016 and MoU SU – LNF-INFN 70-06-497/07-10-2014.

References

[1] W. de Boer [CMS] (2013) The Discovery of the Higgs Boson with the CMS Detector and its Implications for Supersymmetry and Cosmology. arXiv:1309.0721 [hep-ph].

[2] F. Zwicky (1933) Die Rotverschiebung von extragalaktischen Nebeln. *Helvetica Physica Acta* **6** 110–127.

[3] V.C. Rubin, W.K. Ford, Jr. and N. Thonnard (1978) Extended rotation curves of high-luminosity spiral galaxies. IV. Systematic dynamical properties, Sa through Sc. *Astrophys. J. Lett.* **225** L107-L111. DOI: 10.1086/182804.

[4] B. Holdom (1986) *Phys. Lett. B* **166** 196-198. DOI: 10.1016/0370-2693(86)91377-8.

[5] Mauro Raggi, Venelin Kozhuharov (2014) Proposal to Search for a Dark Photon in Positron on Target Collisions at DAΦNE Linac. *Adv. High Energy Phys.* **2014** Article ID 959802. DOI: 10.1155/2014/959802

[6] P. Valente et al. (2017) *J. Phys. Conf. Ser.* **874** 012017.

[7] M. Battaglieri et al. (2017) arXiv:1707.04591 [hep-ph].

[8] M. Raggi (2018) Status of the PADME experiment and review of dark photon searches. *EPJ Web Conf.* **179** 01020. DOI: 10.1051/epjconf/201817901020.

[9] A.J. Krasznahorkay, M. Csatlós, L. Csige, Z. Gácsi, J. Gulyás, M. Hunyadi, T.J. Ketel, A. Krasznahorkay, I. Kuti and B.M. Nyakó, *et al.* (2016) *Phys. Rev. Lett.* **116**(4) 042501. DOI: 10.1103/PhysRevLett.116.042501; arXiv:1504.01527 [nucl-ex].

[10] F. Oliva (2019) Operation and performance of the active target of PADME. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **958** 162354. DOI: https://doi.org/10.1016/j.nima.2019.162354

[11] G. Georgiev, S. Ivanov, V. Kozhuharov, M. Mitev, R. Simeonov and L. Tsankov (2018) In: *2018 IEEE XXVII International Scientific Conference Electronics - ET*. DOI: 10.1109/ET.2018.8549581.

[12] F. Oliva [PADME] (2019) *Nucl. Instrum. Meth. A* **936** 259-260. DOI: 10.1016/j.nima.2018.10.147.

[13] Gabriele Piperno and PADME collaboration (2019) *J. Phys.: Conf. Ser.* **1162** 012031.

[14] C. Taruggi (2019) *Frascati Phys. Ser.* **69** 189-193.