Search for feebly interactive particles: the PADME experiment

Danilo Domenici
on behalf of the PADME collaboration
Dark Sector extension to SM

Standard Model

Quarks: u, c, t, d, s, b
Leptons: e, μ, τ, ν_e, ν_μ, ν_τ
Forces: Z, γ

PORTAL

vector A'
pseudo-scalar ALPs

\[ \mathcal{L} = \frac{\varepsilon}{2} F_{\mu\nu} F'_{\mu\nu} \]

\[ \varepsilon \ll 1 \]

can address g-2, antimatter in cosmic rays, dark matter

DARK SECTOR

dark bosons: Z'
dark fermions: χ', ψ'

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Production mechanisms

\[ e^+ e^- \rightarrow A' \gamma \]

Cross-section enhanced if mass is known

Coupling constant can be extracted

\[ \frac{\sigma(e^+e^- \rightarrow A'\gamma)}{\sigma(e^+e^- \rightarrow \gamma\gamma)} \sim \varepsilon^2 \]
**PADME Technique**

**Production**

**Positron Annihilation into Dark Matter Experiment**

*Produced in $e^+e^-$ annihilation

| positron (beam) $\leftrightarrow$ electron (target) |

**Decay**

*A’ invisible channel

Missing mass technique

$M_{A'}^2 = (\vec{P}_{e^+} + \vec{P}_{e^-} - \vec{P}_\gamma)^2$

*Visible channel in SM particles

$A' \rightarrow e^+e^-$

**Signal**

$e^+e^- \rightarrow A'\gamma$

**Background**

$e^+e^- \rightarrow \gamma\gamma(\gamma)$

$e^+N \rightarrow e^+Ny$

Beam induced
PADME Sensitivity

Visible Channel

No NA48 for leptophilic dark photon

$\alpha_D = 0.5$

Limit extracted from 1501.01867

Credit to Luc Darmé

FFF 2021

Invisible Channel

$M_A < 23.7$ MeV/c$^2$

$\varepsilon^2 > 5 \times 10^{-6}$

$4 \times 10^{13}$ POT

$A' \rightarrow X\bar{X}$

$K \rightarrow \pi\nu\nu$

$B_{\pi\Delta A}, 2017$

Credit to Danilo Domenici

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Dark Photon Signal

$e^+ e^- \rightarrow A' \gamma$

One $\gamma$ and no inactive activity in the detectors
Background: Bremmstrahlung

\[ e^+ N \rightarrow e^+ N \gamma \]

One \( \gamma \) but in time low energy \( e^+ \) in the spectrometer

\[ \sigma = 4b / \text{C atom} \] @ \( E_\gamma = 1\text{MeV} \)
$e^+ e^- \rightarrow \gamma\gamma(\gamma)$

one (or two) $\gamma$ not in detector acceptance

$\sigma = 0.15\text{mb} @ E_\gamma > 1\text{MeV}$
Visible decay

\[ e^+ e^- \rightarrow A' \rightarrow e^+ e^- \]

**Diagram Description:**
- **e^+ beam** enters through the vacuum vessel.
- The **active target** is hit by the **e^+ beam**.
- The decay **A'** is observed, resulting in the production of **e^+** and **e^-**.
- The **e^+** and **e^-** are detected in the spectrometer.
- **Dipole magnet** and **veto detectors** are present to enhance the detection efficiency.
- **TimePix beam monitor** and **BGO calorimeter** are used for high-energy and small-angle measurements, respectively.

**Text:**
- **lepton pair detected in the spectrometer**
the accelerator complex of INFN Frascati National Laboratories

- Energy: up to 550 MeV – 1% spread
- Bunch spacing: 50 Hz
- Intensity: $1 \div 25 \times 10^3$ e$^+$/bunch
- Bunch length: 10 ÷ 200 ns
- Beam spot: $\sigma_{xy} \sim 1$ mm
- Divergence: $\sim 1$ mrad

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the PADME Detector

PbF₂ Cherenkov Small Angle Calo

BGO crystal calorimeter

vacuum chamber with vetoes

diamond sensitive target

positron beam

Mimos a beam monitor

PbF₂ Cherenkov Small Angle Calo

beam exit

Timepix beam monitor

dipole magnet
Diamond Active Target

annihilation target provides single bunch XY profile

provides beam multiplicity

20x20x0.1 mm$^3$ pCVD sensor
16+16 XY graphite strips
1 mm pitch
60 µm charge centroid resolution

10% intensity
Charged Particle Veto

**Bremstrahlung Suppression and Detection of Visible Decays**

- **E veto (96 bars)**
- **P veto (90 bars)**

**HEP veto (16 bars)**

**Plastic Scintillators Bars**
- 10x10x178 mm³
- WLS fiber + 3x3 mm² SiPM
- 700 ps time resolution
- 2% momentum resolution

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**Electromagnetic Calorimeters**

- Detection of annihilation events
- Bremsstrahlung suppression

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**ECAL - Electromagnetic Calorimeter**
- 616 scintillating BGO crystals, 21x21x230 mm$^3$
- PMT readout
- $\sigma E/E = 2.7\%$ at 490 MeV
- BGO decay time = 300 ns
- Radiation length = 20.5 X0

**SAC - Small Angle Calorimeter**
- 25 Cherenkov PbF$_2$ crystals, 30x30x140 mm$^3$
- PMT readout
- PbF$_2$ signal time = 3 ns
- Time resolution = 86 ps
- Rate capability = 40 cluster/bunch
Beam Monitors

**UPSTREAM - MIMOSA**
Monolithic pixel tracker in vacuum
- 19.9x19.2 mm\(^2\) sensor area
- 960x928 pixel array
- 20.7 µm pitch – 0.9 million pixels
- Single point resolution = 3 µm
- Readout time = 200 µs

**DOWNSTREAM - TIMEPIX**
- 2x6 matrix of 14x14 mm\(^2\) Timepix 3
- 0.13 µm CMOS technology
- 256x256 pixel matrix, 55x55 µm\(^2\)
Data Taking

Run 1 POT vs Time

N_{pot/day} = 0.9 \times 10^{11}

Run 2 POT vs Time

PRELIMINARY

RUN1 (Oct 18 – Feb 19)
7 \times 10^{12} POT

RUN2 (Sep 20 – Dec 20)
5.6 \times 10^{12} POT
**Beamline Characteristics**

**RUN1 – Secondary Beam**
- 250 µm Be window
- 545 MeV
- 25kPOT / 250 ns bunch

**RUN1 – Primary Beam**
- 250 µm Be window
- 490 MeV
- 25kPOT / 250 ns bunch

**RUN2 – Primary Beam**
- 125 µm Mylar window
- 430 MeV
- 28kPOT / 280 ns bunch

PADME preliminary

normalised to $1.6 \cdot 10^7$ PoT

normalised to $1.6 \cdot 10^{10}$ PoT

$E_{\gamma_1} + E_{\gamma_2}$ [MeV]
Cluster distribution in PVeto

PADME preliminary

nPOT=9.3x10^9

E_{beam}=490 MeV, 23 ke^+/150 ns bunch

complete screening approximation

beam background measured w/o target and subtracted

bremsstrahlung photon distribution in agreement with simulation and analytical calculation

systematic uncertainties dominated by background normalization, positron momentum scale, POT measurement calibration

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Beamlines Comparison

July 2019, Run1

**PADME** preliminary

nPOT=9.3x10^8, Data July 2019

E_{beam}=490 MeV, 23 ke^2/150 ns bunch

enlarged scale

July 2020, Run2

**PADME** preliminary

nPOT=2.7x10^9, Data July 2020

E_{beam}=450 MeV, 10 ke^2/150 ns bunch

much cleaner distribution evident in Run2

photon energy in calorimeter + e+ energy computed by PVeto position (in time within 1 ns)
Calorimeter Performance

Energy resolution
\[ \sigma_{E/E} = (2.62 \pm 0.05)\% \text{ @ 490 MeV} \]
in 1 POT/bunch calibration run

Testbeam small prototype
INST 15 (2020) no. 10, T10003

Multihit reconstruction in 1 POT/bunch calibration run

Time resolution
\[ \sigma_t \sim 1 \text{ ns} \]
for photons > 100 MeV

\[ N_{e^+} = 1.18 \pm 0.22 \text{ /bunch} \]
**SM Signal Analysis**

**SM Annihilation Signal**
- $\Delta t < 10$ ns
- $\Delta \phi < 25^\circ$
- $\gamma\gamma$ COG < 1 cm from nominal beam

**Powerful Run-Dependent Monitor of the Luminous Point**

**Cross-section Measurement with Clear Run2 Sample in Progress**

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Run3: hunt to X17

$^8$Be anomaly (18 MeV to GS)

$^4$He anomaly (21 MeV to GS)

$m_X = 16.84 \pm 0.16 \text{(stat)} \pm 0.20 \text{(syst)} \text{ MeV}$

$\Gamma_X = 3.9 \times 10^{-5} \text{ eV}$

*PRL 116, 052501 (2016)*


**PADME Run3 (Spring-Summer 2022)**

search for X17 in resonant production with 282.7 MeV e$^+$ beam and e$^+$ e$^-$ decay

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Conclusions

PADME has started to explore the Dark Sector

Run1 (2019) has been very fruitful to understand and optimize the positron beam

Run2 (2020) clean data sample is under analysis to give first physics results

Run3 (2022) will be devoted to the hunt of the hypothetical X17 boson from Be anomaly