Study of the X17 anomaly with the PADME Experiment

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The Dark Sector Paradigm

Standard Model

- Quarks: u, c, t, d, s, b
- Leptons: e, μ, τ, νₑ, νₘ, νₜ
- Forces: Higgs boson, Z, W, G

Portal

\[ \mathcal{L} \sim g_V q_f \bar{\psi}_f \gamma^\mu \psi_f A'_\mu \]

- Feeble interaction with ordinary matter
- \( g_V \ll 1 \)

Dark Sector

- Dark bosons: Z', A'
- Dark fermions: \( \chi' \), \( \psi' \)
- Can address g-2, antimatter in cosmic rays, dark matter
- Can be produced at accelerators
- Can decay back to ordinary matter
Dark Photon Production

electron and positron beam experiments

\[ e^{-} A' \gamma e^{+} \]

\[ e^{\pm} \rightarrow A' \rightarrow e^{\pm} \]

\[ e^{\pm} \rightarrow A' \rightarrow e^{\pm} \]

Associated Production

Resonant production

only positron beam experiments

\[ \sigma_{res}(E_{e^+}) = \frac{12\pi}{m_{A'}^2} \frac{\Gamma_{A'}^2/4}{(\sqrt{s} - m_{A'})^2 + \Gamma_{A'}^2/4} \]

Cross-section enhancement if \( m_{A'} \) known and \( \sqrt{s} = m_{A'} \)

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Dark Photon Decay and Experimental Approaches

Visible decays to SM particles

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

- Thick target electron/proton beam (NA64)
- Thin target beam and search peak in \( e^+ e^- \) invariant mass

Invisible decays

(+ visible but long-lived mediators)

\[ A' \rightarrow \chi \chi \]

- Missing energy/momentum: \( A' \) produced in the interaction of an electron beam with thick/thin target (NA64/LDMX)
- Missing mass: \( e^+ e^- \rightarrow A' (\gamma) \) search for invisible particle using kinematics (Belle II, PADME)
De-excitation of light nuclei via Internal Pair Creation shows anomalous peak in angular distribution of $e^+e^-$

**ATOMKI Spectrometer**

*2016*

\[ m_X c^2 = 17.01 \pm 0.16 \text{(tot)} \text{ MeV} \]

*2020*

\[ m_X c^2 = 16.98 \pm 0.25 \text{(tot)} \text{ MeV} \]
The Hypothetical X17 Boson

All anomalies are explainable with the existence of a new boson dubbed X17 with these characteristics:

\[ m_X c^2 = 16.84 \pm 0.16 \text{(stat)} \pm 0.20 \text{(syst)} \text{ MeV} \]

\[ j^P = 1^- \text{ (vector) or } 1^+ \text{ (axial-vector)} \]

\[ Br(e^+ e^- \rightarrow X_{17}) \approx 5 \times 10^{-6} \]

\[ Br(e^+ e^- \rightarrow \gamma \gamma) \]

\[ \Gamma_{A'} \approx \epsilon^2 \alpha m_{A'}/3 < 10^{-2} \text{ eV} \]
The Frascati LINAC can produce $\geq 10^{10}$ positrons in 20 keV range around $\sqrt{s} = 17$ MeV (beam energy around 282 MeV).

X17 Resonant Production at PADME

ATOMKI decay

$X_{17} \rightarrow e^- e^+ e^- e^+$

No model dependence just electron coupling!

High production rate expected at the resonance

$$\sigma_{peak} = \frac{12}{m^2_{A'}}$$

Extremely small width $\Gamma_{A'} < 10^{-2}$ eV

We need a lot of positrons in a narrow energy range

The Frascati LINAC can produce $\geq 10^{10}$ positrons in 20 keV range around $\sqrt{s} = 17$ MeV (beam energy around 282 MeV)
the accelerator complex of INFN Frascati National Laboratory

- Energy: up to 550 MeV – 1% spread
- Bunch spacing: 50 Hz
- Intensity: $1 \div 25 \times 10^3$ e+/bunch
- Bunch length: $10 \div 300$ ns
- Beam spot: $\sigma_{xy} \sim 1$ mm
- Divergence: $\sim 1$ mrad
A PADME Picture

[2022 JINST 17 P08032]
The PADME Detector

- BGO crystal calorimeter
- vacuum chamber with vetoes
- diamond sensitive target
- positron beam
- PbF$_2$ Cherenkov Small Angle Calo
- beam exit
- Timepix beam monitor
- dipole magnet
- Mimosa beam monitor
Detector: Beam Monitors

Diamond active annihilation target

- Single bunch XY profile and beam multiplicity
- 20x20x0.1 mm$^3$ pCVD sensor
- 16+16 XY graphite strips
- 1 mm pitch
- 60 µm resolution
- 10% intensity measurement

[NIM A 162354 (2019)]

Downstream Timepix

- 2x6 matrix of 14x14 mm$^2$ Timepix3
- 0.13 µm CMOS technology
- 256x256 pixel matrix, 55x55 µm$^2$
Detector: Calorimeter and Tagger

**Electromagnetic Calorimeter (ECAL)**

- BGO crystals: 616, 21×21×230 mm³
- PMT readout
- \(\sigma E/E = 2.8\%\) at 490 MeV
- BGO decay time = 300 ns
- Radiation length = 20.5 \(X_0\)
- [JINST 15 (2020) T10003]

**Electron Tagger (ETAG)**

- 16 scintillators 600x45x5 mm³
- 4 SiPM direct readout on both sides
- Installed in 2022

**bremmstrahlung suppression**

**annihilation events**
Resonant annihilation
\[ e^+ e^- \rightarrow X_{17} \rightarrow e^+ e^- \]
PADME Detector for X17 Boson

Bhabha background
\[ e^+ e^- \rightarrow e^+ e^- \]

- e^+ beam
- Active target
- e^+ veto
- Dipole magnet OFF
- e^- veto
- Vacuum vessel
- e^+ high energy veto
- Electron Tagger
- BGO calorimeter
- TimePix beam monitor
PADME Detector for X17 Boson

$\gamma\gamma$ Background
$e^+e^- \rightarrow \gamma\gamma$

- **e**$^+$ beam
- **e**$^-$/**e**$^+$ veto
- **e**$^+$ high energy veto
- vacuum vessel
- dipole magnet OFF
- **BGO** calorimeter
- **TimePix** beam monitor
- **Electron Tagger**

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X17 Resonance Scan

PADME Run3
September - December 2022
Energy scan around X17 Mass

5 points below resonance: 205 ÷ 211 MeV
Spacing: 1.5 MeV
Statistics: $10^{10}$ POTs/point
Used to validate analysis

47 points on resonance: 263 ÷ 299 MeV
Mass region $16.4 \text{ MeV} < M_{X17} < 17.5 \text{ MeV}$
Spacing: 0.75 MeV (equal to the energy resolution)
Statistics: $10^{10}$ POTs/point
Precision on $M_{X17}$ measurement: ~20 keV

1 point above resonance: 402 MeV
Statistics: $2 \times 10^{10}$ POTs
Used to validate NPOT measurement

Signal should emerge on top of Bhabha and $\gamma\gamma$ backgrounds
First Look at Off-Resonance Data

Selection of 2 clusters in ECAL within 5ns (no need to rely on Etag efficiency)

\[ N(e^+e^- + \gamma\gamma) \]

\[ \frac{N}{N_{POT}} \]

\[ \begin{array}{c}
\frac{N(e^+e^-)}{N_{POT}} \\
\frac{N(\gamma\gamma)}{N_{POT}} \\
\frac{N(e^+e^-)}{N(\gamma\gamma)}
\end{array} \]

Energy vs Angle compatible with a 2 body final state.

Existence of X17 and its spin-parity can be assessed

RMS ~0.7% over 5 runs compatible with pure statistics

Above Resonance: 402 MeV
X17 Expected Limits

- We made a unique scan with width of blue and density of green.
- New plots coming soon.

Darmé et al. Phys. Rev. D 106,115036
Conclusions

In 2022 the PADME experiment, with a modified setup, was dedicated to the search of X17 with resonant production of a positron beam on target.

Energy scan performed in range 16.35 MeV < M_{X17} < 17.5 MeV

Current analysis on off-resonance data shows < 1% observable stability and very good background separation.

Next step is move to sidebands closer to M_{X17}.

PADME results on X17 coming soon. Stay tuned!
SPARES
**Detector: Vetoes and SAC**

**Electron-Positron Vetos**

**EVETO-PVETO**

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

**bremmstrahlung suppression**

**detection of visible decays**

- plastic scintillators bars
  - 10x10x178 mm$^3$
- WLS fiber + 3x3 mm$^2$ SiPM
- 500 ps time resolution
- 2% momentum resolution
  - [NIM A 936 (2019) 259]
  - [JINST 15 (2020) 06, C06017]

**HEP veto**

- (16 bars)

**Small Angle Calorimeter**

**SAC**

- 25 Cherenkov PbF$_2$ crystals
  - 30x30x140 mm$^3$
- PMT readout
- PbF$_2$ signal time = 3 ns
- Time resolution = 80 ps
- Rate capability = 40 cluster/bunch
  - [NIM A 919 (2019) 89]
Data Taking Runs

RUN1 – 2019
Secondary Beam
$7 \times 10^{12}$ POT
250 µm Be window
545 MeV
25kPOT / 250 ns bunch

RUN2 – 2020
Primary Beam
$6 \times 10^{12}$ POT
125 µm Mylar window
430 MeV
28kPOT / 280 ns bunch

RUN3 – 2022 – X17 search
Primary Beam
$6 \times 10^{11}$ POT
125 µm Mylar window
283 MeV
2kPOT / 260 ns bunch
Energy beam selection and Resolution

First dipole used to select energy
Second dipole used to correct trajectory and center beam on PADME axis
Measure displacement with TimePix to compute energy step
Physics case:
- known only with 20% accuracy below 0.6 GeV
- Most recent measurement is 60 y old
- Used data of Run2

\[ \sigma(e^+ e^- \rightarrow \gamma \gamma) = (1.930 \pm 0.029_{\text{stat}} \pm 0.156_{\text{syst}}) \text{ mb} \] most precise measurement in this energy regime