The PADME calorimeters for missing mass dark photon searches

F. Ferrarotto

INFN Sezione Roma 1

on behalf of the PADME Collaboration

INFN Roma, INFN Frascati, INFN Lecce, MTA Atomki Debrecen, University of Sofia, Cornell University, US William and Mary College

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Lyone
Why the PADME experiment?

Long standing problem: large cosmological evidence for existence of dark matter (DM), but no clear experimental observation.

Without modifying the SM structure $U(1)_Y + SU(2)_L + SU(3)_C$ DM can’t be strong interacting (scattering cross section too high) or electrically charged
- can be weakly interacting and massive (WIMPs)
  BUT ... no observation up to now
strong constraints from LHC and direct searches at masses up to TeV

Introduce a new “hidden“ sector?
- Need new mediator particle, very weakly interacting with SM particles, connecting to DM sector
- can be light (where direct detection gets into trouble)
- can explain anomalies in muon magnetic moment, results from scattering experiments searches for DM and antimatter excess in cosmic rays.

End of 2015: INFN approved a new experiment at the DAΦNE Linac Beam Test Facility (BTF) at Frascati National Laboratories (LNF):
  PADME (Positron Annihilation into Dark Matter Experiment)
The dark photon

**Simplest** hidden sector model: one extra U(1) gauge symmetry and a new gauge boson: “dark photon” or U boson or heavy photon (γ' or A')

**Two types** of interactions with SM particles to be considered:

1. QED-like: interactions of the type \[ \mathcal{L} \sim g' q_f \bar{\psi}_f \gamma^\mu \psi_f U'_\mu \]
   - Not all SM particles need to be charged under this new symmetry
   - In most general case \( q_f \) may be different between leptons and quarks

2. Coupling to SM hypercharge through kinetic mixing operator, acquiring a (small) SM charge
   - \( \frac{1}{2} \varepsilon F_{\mu\nu} F'^{\mu\nu} ; F'^{\mu\nu} = \partial_\mu A'_\nu \)
   - \( A'_\mu \to A_\mu + \varepsilon a_\mu ; \alpha' = \varepsilon^2 \alpha \)

If **no** DM particles with \( m_{DM} < m_A'/2 \) exist:
- \( A' \to SM \) **visible decays** with (likely) \( BR \approx 1 \)
- \( A' \) lifetime proportional to \( 1/(\alpha' \varepsilon^2 m_A') \)

If DM particles with \( m_{DM} < m_A'/2 \) exist:
- \( A' \to DM \) **invisible decays** with (likely) \( BR \approx 1 \)
- SM decays suppressed by a factor \( \varepsilon^2 \)
- \( A' \) lifetime \( \approx 1/(\alpha'_D m_A') \) \([\alpha'_D : A' \) coupling constant to the Dark Sector]
**The PADME approach**

PADME proposes a new technique: **annihilation** of a **positron** beam on a (thin, low Z) target, search for a peak in missing mass at $M^2_{\text{miss}} \neq 0$ (invisible decay) calculated from final state $\gamma$ 4-momentum in kinematically constrained condition.

- well known beam energy and position
- measure photon energy and position

$$m^2_{\text{Miss}} = (P_{\text{beam}} + P_{e^-} - P_{\gamma})^2$$

PADME can explore in a **model independent way** the region down to $\varepsilon \approx 10^{-3}$

$$m_{A'} < 23.7 \text{ MeV (} E_{\text{beam}} = 550 \text{ MeV)}$$

- minimal model dependent assumptions: $A'$ couples to SM
- coupling of any new light particle produced in $e^+e^-$ annihilation can be limited:  
  **Dark Photon, Axion Like Particles, Dark Higgs, new proto-phobic vector boson**, ...

The detector layout (3D view)

Active diamond target
100 µm thick
x,y graphite strips r/out
Beam size, position, time , Ne⁺

Positron veto
Scintillators 1×1 cm²
r/out SiPM

Electron veto
Scintillators 1×1 cm²
r/out SiPM

"Golden signal" event:
1 single γ in EM calo
Nothing in all other components in ±2 ns

Calorimeter material choice crucial
Backgrounds

e/p/HEP Vetos and SAC essential to veto backgrounds

Signal selection cuts:
- 1 cluster in ECAL fiducial volume
- no hits in e/p/HEP vetoes in ± 2 ns
- no γ in the SAC $E_γ > 50$ MeV in ± 2 ns
- Cut 20-150 MeV < $E_γ$ < 120-350 MeV (depending on $m_{A'}$)
EM Calorimeter choice

3 basic requirements for the calorimeter:

1. Measure $E_\gamma$, $\theta_\gamma$
   - Good energy resolution: 1-2%/\sqrt{E} [GeV]
   - High Photo-statistics
   - Good containment
   - Good angular resolution: $\approx$1 mrad

2. Fight pile-up and backgrounds
   - Sub-ns timing resolution

Choice limited to:
- LYSO ($R_M = 2.07$ cm)  
  Best choice - expensive
- BGO ($R_M = 2.23$ cm)  
  2. best

Obtained for free from the L3 calorimeter part of the EC BGO crystals thanks to an agreement between INFN, the L3 Coll. and Prof. Ting

Crystals dismounted and annealed at CERN
Reworked to get usable size and shape for PADME

Crystal cost: 50 k€ (BGO) vs 2 M€ (LYSO) (!)
The EM Calorimeter

**BGO** - high LY, high $\rho$, small $X_0$ and $R_M$, long $\tau_{\text{decay}}$

- 616 crystals each 21x21x230 mm$^3$
- Crystal depth = 20.5 $X_0$

- Shape ~ cylinder $R \sim 285$ mm
  - Front face at 3 m from active target

- Magnet dipole gap limits angular coverage: [20,93] mrad

- Fiducial volume angular acceptance: [26,83] mrad

- Inner hole ~ 105x105 mm$^2$ wide square for vetoing backgrounds (faster SAC calorimeter)

- Readout by HZC XP1911 PMT
  - 19 mm $\varnothing$ good coverage of crystal
**EM Calorimeter performances**

**Expected Performances:**
- $\sigma(E)/E \sim 1-2\%/\sqrt{E}$
- $\sigma(\theta) < 1\ mrad$
- Timing : $< 1\ ns$ from signal shape fit

### Missing mass squared resolution

![Graph showing MMiss$^2$ for different M$^*_K$](image)

### Crystal signal at 1 GS/s

![Graph showing Crystal signal at 1 GS/s](image)

### Full digitization of signals over $\sim 1\ \mu$s ($\sim 3\ \tau_{\text{BGO}}$) with CAEN V1742@1GS/s

![Diagram of full digitization setup](image)

- **BTF beam trigger (max 49 Hz)**
- **CAEN V1742 waveform digitizer 1-5 GS/s**
- **BGO matrix**
- **HZE XP1912**
- **Optical fiber**
- **PC Linux**

*2/10/2017  F. Ferrarotto - CHEF 2017*
EM calo 2016 beam test

5x5 crystal prototype, HZC 1911 PMTs at LNF BTF
(Average) single particle e\(^+\) beam mostly – 10 ns bunch@49 Hz
Crystals wrapped white Teflon tape – PMT coupled w/ opt grease
2016 test results published in *NIM. A 862 (2017) 31-35*
Crystal response ~ 16 pC/MeV

\[
a\sqrt{E} \oplus b/E \oplus c
\]

\[
\chi^2/\text{ndf} = 6.499/3
\]
\[
a = 0.02013 \pm 0.001632
\]
\[
b = 2.954e-05 \pm 1.306e-05
\]
\[
c = 0.01152 \pm 0.002914
\]

E resolution
Test beam vs MC

Linearity
E < 1 GeV

250 MeV and multiples
450 MeV and multiples
Improvements 2017

Improvements before 2017 Tests:
- PMT glued (optical glue) on crystals before painting
- 100 μm paint OK for light tightness at few % level
- Studies with cosmics: need to add TEDLAR foils (50 μm) to drop optical cross-talk to zero
- Calibration using Co and Na$^{22}$ sources

Final element crystal+PMT painted and mounted

Cosmics run with Tedlar
Crystal Q with vertical passing track vs left crystal Q
Shown only 4/25 crystals
No slope (expected by optical xtalk)

Radiation damage tests done:
- No significant radiation damage on PMT
- Radiation damage on BGO observed at dose levels expected from literature
- Damage recovered by high temperature annealing
Improvements 2017

Improving pedestal calculation precision essential for zero suppression and better resolution at lower energies
Foreseen random trigger for pedestals between 49 Hz events (not yet in BTF tests)

- Average of 1000 bins: better estimate of the pedestal!
- Avg 100 bins
- Mean pedestal with 0.2 pC precision!
- Gaussian pedestal average $\sigma=1.3$ pC
- With 16 pC/MeV crystal response $E_{\text{thr}} \sim 0.35$ MeV
- 100 MeV $e^+$

Na$_{22}$ calibration w/ new pedestal

Very good spectrum for low energy $\gamma$ with reasonable energy scaling. End point $\sim 20$ MeV
EM calo 2017 beam test
preliminary

4x3 and 5x5 crystal prototypes tested, HZC 1911 PMTs at LNF BTF
(Average) single particle $e^+$ beam mostly – 10 ns bunch@49 Hz
Energy scan 100-400 MeV in 50 MeV bins

New ped calc used
$4 \sigma \sim 5$ pC zero suppr

Very good multipart separation
$E = 100$ MeV

Painted and glued crystal + PMT
Tedlar foils between crystals

Final analysis in progress
Preliminary:
Energy resolution at 100 MeV ~ 7%
The SAC calorimeter

Basic requirements: **FAST, compact** calorimeter
- measure $E_y$ from $\sim 50$ MeV at very high rates: several*10 $\gamma$ in 200 ns
- avoid scintillation mechanism ($\tau$ too long) → Cherenkov light
- good time resolution needed $O(\leq 200)$ ps → very fast photosensors
- no need for high light yield material: 0.5 - 2 p.e./MeV is OK
- radiation tolerant (order 1 Gy per $10^{13}$ $e^+$ on target)
- moderate energy resolution $O(5-10 \%) /\sqrt{E}$
- transparency at shorter wavelengths (higher Cherenkov yield)

Choice: 5x5 matrix of 30x30x140mm$^3$ PbF$_2$ crystals

Readout: Hamamatsu R13478 PMT (BA): fast ($< 1$ ns risetime) - 2.54 mm Ø (56% coverage)
Scale of 1-2 p.e./MeV expected
Black wrapping of crystal to avoid reflections inside

2017 BTF beam test
Black wrapped single PbF$_2$ crystal
Signal digitization at 5 GS/s by CAEN V1742
with improved dynamic range: 0-2 V

Very good particle separation with $\sim 2$ ns spacing
SAC performances - preliminary

Test beams performed an LNF BTF in 2017 – 100-400 MeV e\textsuperscript{+} - single PbF\textsubscript{2} crystal

Measured light yield ~ 1.5 p.e. /MeV  OK for us

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Integrated Charge - Channel 0 (PbF\textsubscript{2}) - Run 846

Very good multipart peak separation

200 MeV e\textsuperscript{+}

Linearity up to GeV

Very good time resolution < 100 ps at all energies

Energy resolution

O(10%) E resol

phe statistics

leakage
## Running program

Expect to finish installation by end of 2017
Commissioning during first 3 months of 2018
Expect to have ~ 6 months of physics runs in 2018
to get $10^{13}$ POT (possibly using 200 ns bunch)

6 months data taking with 50% efficiency - bunch length 200 ns – $2.5 \times 10^3$ e$^+$/bunch

$10^{13}$ POT $\sim 25000$ e$^+$/bunch $\times 7.8 \times 10^6$s $\times 49$ Hz

Possible extension of data taking in 2019

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Conclusions

- Dark Photon (DP) is predicted in new class of general new physics models with a “hidden” sector.
- PADME will search for an “invisible” DM decaying DP at the new dedicated BTF line at the Linac of Laboratori Nazionali di Frascati.
- We have made beam tests at LNF BTF in 2016 and 2017 for all the main detector components: all behave as expected from design. We are starting the construction phase.
- Schedule: building within end of 2017 and 6 month data taking on new dedicated BTF line at LNF in 2018 (possibly also 2019).
- Results will apply also to other hypothetical light particles like Axion Like Particles, Dark Higgs, new proto-phobic vector boson.

A very exciting time awaits us all!
You are welcome to join “the dark side“!
References

Dark Photon

Dark Photon and \( (g-2)_\mu \) anomaly
• M. Pospelov, Phys. Rev. D 80, 095002 (2009)
• J. P. Lees et al., arXiv:1702.03327 (2017)

Dark Photon research status and perspectives
• M. Battaglieri at al., arXiv:1707.04591v1

ALPs and \( (g-2)_\mu \)

Be anomaly - Fifth force
• A. J. Krasznahorkay et al., PRL 116, 042501 (2016)
• Jonathan L. Feng et al., PRL 117, 071803 (2016)

PADME
• M. Raggi and V. Kozhuharov, AdHEP 2014, 959802 (2014)
• M. Raggi, V. Kozhuharov and P. Valente, EPJ Web Conf. 96, 01025 (2015)
• M. Raggi et al., NIM. A 862 (2017) 31-35