Search for dark photon in positron annihilations at Frascati: the PADME experiment

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For the PADME experiment
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Overview

- Dark photon basics
- PADME experiment
- Physics reach
- Present status and activities
- Conclusions
The effective interaction that can be studied is
\[ \mathcal{L} \sim g' \bar{\Psi} (\gamma_\mu + \alpha'_a \gamma_\mu \gamma^5) \Psi A'_\mu, \text{ usually } \alpha'_a = 0 \]

Production mechanisms

Such textbook scenario could address the \((g_\mu - 2)\) discrepancy, abundance of antimatter in cosmic rays, signals for DM scattering
- General \(U'(1)\) and kinetic mixing with \(B (A', Z')\)
  - Universal coupling proportional to the \(q_{\text{em}}\)
  - Just single additional parameter – \(\varepsilon\)
- Leptophilic/leptophobic dark photon

Rich dark sector, contributing to DM explanation
Heavy/Dark photon/boson searches

- Beam dump experiments: $A'$-strahlung production
- Fixed target: peaks in the $e^+e^-$ invariant mass spectrum
- Meson decays: Peaks in $M_{e^+e^-}$ or $M_{\mu^+\mu^-}$
Invisible A' searches

• Really model independent addressing of the dark gauge boson parameters is difficult
• Four parameter space to be studied: $M_{A'}$, $g'$, $g_D$, $M_Z$
  – $g'$ could also be flavour dependent
How to improve?

- Searching a dark photon in a kinematically constraint event and using full reconstruction
- Basic process: positron on a fixed target
  
  \[ e^+ + e^- \rightarrow \gamma + U \left\{ \begin{array}{l} 
  \gamma + E_{\text{miss}} \quad \text{(invisible channel, A' \rightarrow \chi\chi)} \\
  \gamma + e^+e^- \quad \text{(visible channel, A' \rightarrow e^+e^-)} 
  \end{array} \right. \]

- Normalizing to the concurrent process - **annihilation**

\[
\frac{\sigma(e^+e^- \rightarrow \gamma A')}{\sigma(e^+e^- \rightarrow \gamma \gamma)} = \frac{N(\gamma A')}{N(\gamma \gamma)} \times \frac{\text{Acc}(\gamma \gamma)}{\text{Acc}(\gamma A')} = \varepsilon^2 \ast \delta
\]

- \( N(\gamma A'), N(\gamma \gamma) \) - number of registered events
- \( \text{Acc}(\gamma A'), \text{Acc}(\gamma \gamma) \) - detection efficiency
- \( \delta = \sigma(e^+e^- \rightarrow \gamma A')/\sigma(e^+e^- \rightarrow \gamma \gamma) \) at \( \varepsilon=1 \) – cross section enhancement factor
Basic ideas

Electron is at rest

Positron momentum is determined by the accelerator characteristics

Basic contribution to the missing mass resolution – reconstruction of the photon 4-momentum
  – Interaction point inside the target
  – Cluster position in the calorimeter
  – Energy resolution of the calorimeter

Background suppression
  – Veto on extra particles

\[
M_{\text{miss}}^2 = (p_{\text{pos}} + p_{\text{elec}} - p_\gamma)^2
\]

Study only the recoil photon

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DP model

- Simple model implemented in CalcHEP, used for the further studies
  
  \[ \mathcal{L} \sim \varepsilon \bar{e} e \gamma_\mu e A'\, e, \text{only for } e^\pm \]

- Validate with \( A' \) decay rate into \( e^+e^- \)

\[
\Gamma_U = \Gamma_{U \rightarrow e^+e^-} = \frac{1}{3}\alpha\varepsilon^2 M_U \sqrt{1 - \frac{4m^2}{M_{H^2}} \left( 1 + \frac{2m^2}{M_{H^2}} \right)}
\]

For \( \sqrt{s} \gg M_A \), \( \sigma(e^+e^- \rightarrow \gamma A') = 2 \cdot \varepsilon^2 \cdot \sigma(e^+e^- \rightarrow \gamma\gamma) \)
### BTF @ LNF

**Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Parasitic mode</th>
<th></th>
<th>Dedicated mode</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>With target</td>
<td>Without target</td>
<td>With target</td>
<td>Without target</td>
</tr>
<tr>
<td><strong>Particle species</strong></td>
<td>e(^+) or e(^-)</td>
<td>e(^+) or e(^-)</td>
<td>e(^+) or e(^-)</td>
<td>e(^+) or e(^-)</td>
</tr>
<tr>
<td></td>
<td>Selectable by user</td>
<td>Depending on DAFNE mode</td>
<td>Selectable by user</td>
<td></td>
</tr>
<tr>
<td><strong>Energy (MeV)</strong></td>
<td>25–500</td>
<td>510</td>
<td>25–700 (e(^-)/e(^+))</td>
<td>250–730 (e(^-) 250–530 (e(^+))</td>
</tr>
<tr>
<td><strong>Energy spread</strong></td>
<td>1% at 500 MeV</td>
<td>0.5%</td>
<td>0.5%</td>
<td></td>
</tr>
<tr>
<td><strong>Rep. rate (Hz)</strong></td>
<td>Variable between 10 and 49</td>
<td>Depending on DAFNE mode</td>
<td>1–49</td>
<td>Selectable by user</td>
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<tr>
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</tr>
<tr>
<td><strong>Pulse duration (ns)</strong></td>
<td>10</td>
<td></td>
<td>1.5–40</td>
<td>Selectable by user</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Intensity (particles/bunch)</strong></td>
<td>1–10(^5) Depending on the energy</td>
<td>10(^7)–1.5 10(^10)</td>
<td>1–10(^5) Depending on the energy</td>
<td>10(^3)–3 10(^10)</td>
</tr>
<tr>
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<tr>
<td><strong>Max. average flux</strong></td>
<td></td>
<td>3.125 10(^10) particles/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Spot size (mm)</strong></td>
<td>0.5–25 (y) × 0.6–55 (x)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td><strong>Divergence (mrad)</strong></td>
<td>1–1.5</td>
<td></td>
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</tr>
</tbody>
</table>

- Small beam energy spread
- Available immediately
- Possibility to make modifications to optimize the conditions

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PADME experiment

Positron Annihilation into Dark Matter Experiment

- Small scale fixed target experiment
- Measuring both charged and neutral particles:
  - Charged particles detector
  - Calorimeter
  - Beam profile
Beam

“single” particle

\[ \langle N \rangle = 2000 \]

\[
\begin{align*}
\text{RMS}_x &= 0.9 \text{ mm} \\
\text{RMS}_y &= 0.9 \text{ mm}
\end{align*}
\]

\[
\begin{align*}
\text{RMS}_x &= 1.9 \text{ mm} \\
\text{RMS}_y &= 1.1 \text{ mm}
\end{align*}
\]

\[ M_{A'} = 5 \text{ MeV} \]

2m from target

4m from target

CALO: \( \sigma_x = \sigma_y = 2 \text{ mm} \)

- \( 10^3 \) – \( 10^4 \) e\(^+\)/bunch can be achieved by adjusting the collimators
  - Divergence
  - Energy spread

**Optimization**
The nominal positron convertor is after the first section of the Linac, limiting the maximum $e^+$ energy up to 550 MeV.

- $10^{10}$ primary electrons/bunch, $10^4$ $e^+$ necessary for PADME
  - Possible to use the BTF target to produce positrons
Active target

- Graphitized diamond – strips of 1mm width
  - All carbon target
- The production of 50 μm detector is state-of-the-art
  - 2 cm x 2 cm
  - Samples produced, 2x 50 μm thickness, 1 x 100μm thickness
- To be tested at BTF in November
BTF test run in October, 2014

- 500 um, metal strips: 6.5 mm long, 1.5 mm pitch
- 300 um, graphitized strips: 3 mm long, 100 um width
- 50 um, 2 cm x 2 cm: first sample for PADME
- 50 um, silver paint: 5 mm x 5 mm

Poly Diamond Digitized Waveforms at BTF with HV=300V and 300e-/bunches

- Backplane
- Strip 1
- Strip 2
- Strip 3
- Strip 4

Estimated CCD = 10-20 um
• Cylindrical shape
• LYSO was assumed to be the best solution and was used as a baseline for estimating the sensitivity
  – Located 2m downstream the target
  – 656 LYSO crystals. 1x 1 x 15 cm$^3$
• Energy resolution: $\sigma E/E = \frac{1.1\%}{\sqrt{E}} \oplus \frac{0.4\%}{E} \oplus 1.2\%$
• Possible substitutions under investigation: BGO
• BGO crystals available from L3 experiment

• Crystal geometry is close to 2 x 2 cm front face
  – Cut the crystals in 1 x 1 cm and place them at 2 m
    • Requires cutting of the existing crystals, but the quantity is identified and available
  – Place the calorimeter at 4 m distance and keep the dimensions 2x2 cm
    • Agreement on the usage of extra crystals
BGO crystals

• Single L3 crystal cut into 4 1cm x 1cm crystals
• Primary solution for the calorimeter
  – Only 164 BGO crystals required
• If more crystals available -> bigger calorimeter
Test run at BTF

3x3 matrix tested at BTF in May
- PMT R6427
- RO: CAEN V1742 digitizer @ 1GS/s
- Study the signal shape
- Reconstruct pulses
- Address saturation

A fit on the signal leads to proper energy deposit determination
Test with APD and SiPM foreseen
Magnet

- CERN spare magnet: MBP-S
- To be refurbished from CERN and transported to LNF
- Usage of the DAΦNE PS: 400A

Charged particle detector
- Plastic scintillator detector
  - SiPM based readout
  - FEE electronics & power supply
Sensitivity

- Full GEANT4 simulation:
  - Calorimeter
  - Target
  - Beam structure (time and spatial)
- Tracker only as a coordinate detector
- Uniform magnetic field
**Background**

**Selection**

- Kept as simple as possible
- Attempt for a common selection of visible/invisible scenarios

- Single cluster in the Calo
- $5 \text{ cm} < R_{cl} < 13 \text{ cm}$
- Cluster energy:
  - $E_{CL}^{\text{min}}(M_{A'})$ in 50 – 150 MeV
  - $E_{CL}^{\text{max}}(M_{A'})$ in 120 – 350 MeV
- Kinematics
  - $\pm 1\sigma$ cut on the missing mass
- Veto on positrons
- Background: $2\gamma$, $3\gamma$, bremsstrahlung
Sensitivity estimation

Assumptions:
- 40 ns bunch length
- 49 Hz repetition
- 6000 $e^+/\text{bunch}$

Accessible regions:
- $E=550\text{MeV}$: $M_{A'} < 23.7 \text{MeV}$

Improvements possible:
- Increase beam energy
- Extend the bunch length
PADME extended programme

conventional electron beam and A'-strahlung: $e^- Z \rightarrow e^- Z A'$

A' → l^+l^- visible decay search

- Measuring l^+l^- momentum with a spectrometer
- Selection based on $M_{l^+l^-}$

Beam dump experiment

Visible decays in $e^+ + e^- \rightarrow \gamma + A' \rightarrow \gamma + e^+ + e^-$

- ~High acceptance (high boost of the produced A' and deflection in the magnet)
  - ~2 times more sensitivity

- Better invariant mass resolution
- Missing mass of $\gamma$ constraint
- Sensitivity: $\epsilon \sim 10^{-7}$
- The first channel to look at if excess of events is observed
PADME visible decays

conventional electron beam and $A'$-strahlung: $e^- Z \rightarrow e^- Z A'$

$A' \rightarrow e^+ e^- $ visible decay search

Beam dump experiment: $A' \rightarrow e^+ e^- $ and $A' \rightarrow \mu^+ \mu^-$

Extend $M_{A'}$ sensitivity, but model dependent

preliminary
The PADME experiment Technical Proposal

The PADME Collaboration

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September 25, 2015
Conclusions

- PADME is a small scale fixed target experiment to search for dark photons in the invisible channel.
- Interesting parameter space could be covered, using $10^3 - 10^5$ e$^+$/bunch.
- Test beam and initial studies already ongoing
- A portal for a complete physics program devoted to the dark photon searches is open – visible, invisible, thin target, thick target, dump, electron or positron

- PADME was endorsed by CSN1 for full financing inside the WhatNext INFN programme

Starting construction next year
SPARE
Additional elements could be added in case of necessity (or profit)
Spectrometer technology

- CERN available magnet versus special magnet design

Detector technology

- GEM based detector
  - 5 layers of triple GEMs on each side or TPC with GEM readout
- Plastic scintillator detector
  - Correlation between longitudinal impact and track momentum
  - Strips versus fibers, SiPM readout vs CCD readout (50 Hz events)
- Other alternatives also in consideration

0.6 T.m in simulation

~ 0.8 T possible for aperture 20cm
Present limits: invisible searches

- There is no published direct present limit in the $U \rightarrow \text{invisible}$ decay – from $a = \frac{g_{-2}}{2}$
- The discrepancy is not in $g_{\mu}^{-2}$ itself, it's in the consistency of $g_e$ & $g_{\mu}$
- Alternative inputs should be used to extract information from $g_e$: $\alpha_{EM}$

Anomalous magnetic moment limits
- $\alpha_{EM}$ usually a determined from $g_{e}^{-2}$ - input
- Used further to constrain $g_{\mu}^{-2}$
- Dark photon contribution:
  \[ \delta a = \frac{\alpha_{EM} e^2}{2 \pi} \times f, f = \begin{cases} 1, \text{for } m_1 \gg M_U \\ \frac{2m_1^2}{3M_U^2}, \text{for } m_1 \ll M_U \end{cases} \]

\[
\alpha^{-1} = 137.035 999 037 (91)
\]

\[
|a_e^{\text{th}} - a_e^{\text{exp}}| = (1.06 \pm 0.82) \times 10^{-12}
\]


The invisible search removes any assumption apart from coupling to leptons!
Direct search experiment

- DAMA/LIBRA results unexplained: 9.2 σ
- Used to be alone, now few other indications emerged
- Seem to be possible to build a consistent picture
- If the explanation is Dark Matter, it should be relative light: ~10 GeV
- Interaction with the nuclei through a mediator. Mass in the MeV range is OK
**Astrophysics** ...

- Positron excess: PAMELA, FERMI, AMS02
- Now also new results from AMS on the antiproton

... and astronomy

Observation of 3.5keV line?
- arXiv:1402.2301
- arXiv:1402.4119
- Possible interpretation: arXiv:1404.2220
- If Dark Matter is the explanation to the positron excess, then the mediator should be light ($< 2^* M_{\text{proton}}$)

- Coupling constant to DM could be arbitrary (even $O(1)$)

- The Lagrangian term can arise through
  - fermions being charged (mili) under this new gauge symmetry ($q_f \rightarrow 0$ for some flavours)
  - Kinetic mixing between ordinary photon and DM one:
    $$\mathcal{L}_{\text{mix}} = -e F_{\mu \nu}^{QED} F_{\mu \nu}^{\text{dark}}$$
  - Using simply an effective description: $g' q'_e = \epsilon$, $\alpha' = \alpha \epsilon^2$
• About 3 $\sigma$ discrepancy between theory and experiment (3.6 $\sigma$, if taking into account only $e^+e^- \to$ hadrons)

$$
a_{\mu}^{\text{dark photon}} = \frac{\alpha}{2\pi} \varepsilon^2 F(m_V/m_\mu),$$

where $F(x) = \int_0^1 2z(1-z)^2/[(1-z)^2 + x^2 z] \, dz$. For values of $\varepsilon \sim 1-2 \cdot 10^{-3}$ and $m_V \sim 10-100$ MeV, the dark photon, which was originally motivated by cosmology, can provide a viable solution to the muon $g - 2$ discrepancy. Searches for the dark