A search for massless dark photons in positronium decays

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Dark Matter: Astro + Cosmology through **Gravitational effects**

**GALACTIC ROTATION CURVES**

**GRAVITATIONAL LENSING**

**COSMIC MICROWAVE BACKGROUND**

$\Lambda$CDM (Lambda Cold Dark Matter)

- Dark Energy: 68%
- Standard Model: 27%
- Dark Matter: 5%
Interaction DM-SM other than gravity? If so very weak…

Only gravitationally? Nightmare scenario from a particle physicist point of view.

\[ \Omega_{DM} \sim 5\Omega_{SM} \]

Relic densities of Standard Matter (SM) and Dark Matter (DM) are “similar”

SUGGESTS COMMON ORIGIN BETWEEN SM and DM.

Can those be related with A SINGLE THEORY?
The vector portal - Dark photons


FOCUS OF THIS TALK

NEW FORCE CARRIED BY A NEW VECTOR BOSON: DARK PHOTON
Signatures for Dark Photons at Fixed target exp. (NA64@CERN)

Visible Decay Mode $m'_A < 2m_X$

- Pair production of SM particles

NA64, Phys. Rev. Lett. 120, 231802 (2018)

Invisible Decay Mode $m'_A > 2m_X$

- Missing Energy/momentum

NA64, Phys. Rev. Lett. 118, 011802 (2017),
NEW: arXiv:1906.00176
The Massless Dark photon case - the Mirror Sector

Parity violation in weak interaction

The Massless Dark photon case - the Mirror Sector

Parity violation in weak interaction


W. Pauli in a letter to V. Weisskopf,
"Now after the first shock is over, I begin to collect myself. Yes, it was very dramatic."
Is Nature left-right asymmetric?

- In the standard model parity violation introduced from beginning in the Lagrangian.

\[
\begin{pmatrix}
  v_l \\
  l_l \\
  u_R \\
  d_R
\end{pmatrix}, \quad \begin{pmatrix}
  l_l \\
  u_R
\end{pmatrix}, \quad \begin{pmatrix}
  u_l \\
  d_R
\end{pmatrix}, \quad u_R, d_R
\]

- Is nature really left-right asymmetric or do we happen to live in a universe dominated by particles with such properties?

1. Left-right symmetric models, symmetry restored at higher energies (V+A suppressed by heavy $W_R$ mass)

2. Postulation of the existence of a sector of mirror particles
   Lee and Yang, Phys. Rev. 104, 4 (1956)
The mirror sector

Ordinary particle sector

<table>
<thead>
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<th>e'</th>
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<tr>
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<td>W, Z</td>
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<td>γ</td>
<td>γ'</td>
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Mirror particle sector

→ Mirror particles: same properties of ordinary particles but chirality of fields inverted.
→ Same micro-physics governs interactions among mirror particles but they experience V+A weak interaction.
If such a sector of particle exists
→ mirror symmetry conserved
→ left-right symmetry of nature restored

The mirror sector

If such a sector of particle exists
→ mirror symmetry conserved
→ left-right symmetry of nature restored


- Doubling the number of elementary particles to solve problems seems to be unnatural … but … it has been done before!
- Relativity + QM ⇒ anti-matter
The mirror sector would interact through gravitation with us. → Mirror particles (stable and massive) are very good dark matter candidates.
The mirror sector could interact through photon mirror-photon kinetic mixing:

→ Implications for cosmology.

→ Bounds (LSS, CMB, BBN): mixing strength $\epsilon < 3 \times 10^{-8}$

Positronium as a portal to the Mirror sector

Coupling between oPs and oPs’ ⇒ breaking of degeneracy

\[ o-Ps^+ = \frac{1}{\sqrt{2}} (o-Ps^+ + o-Ps^{'}) \]
\[ o-Ps^- = \frac{1}{\sqrt{2}} (o-Ps^- - o-Ps^{'}) \]

\[ \Delta E = 2 h \varepsilon \nu \]

Energy splitting

Rabi oscillation:

\[ P(o-Ps \rightarrow o-Ps^{'}) = \sin^2(2\pi \varepsilon \nu t) \]
Experimental signature: \( \text{oPs} \rightarrow \text{invisible decay (missing energy)} \)

**Standard model decay:**

\[ \text{o-Ps} \rightarrow 3\gamma \]

→ energy deposition of 1022 keV (Ps mass, \( E = mc^2 \))
Invisible decay: $o$-Ps → $o$Ps' → $3\gamma'$
→ no energy deposition (event compatible with 0 energy)
Search for oPs → invisible decay (aerogel experiment)


No events in the signal region
→ Upper bound : $\text{Br}(\text{oPs} \rightarrow \text{invisible}) \leq 4.2 \times 10^{-7}$
→ Stringent limit on physics beyond the standard model

o-Ps → $3\gamma$
→ $E_{\text{SUM}} = 1022$ keV
Search for oPs → invisible decay (aerogel experiment)


Aerogel target, SiO2 grains 100 nm

Collisions with matter destroy coherence of oscillation suppressing $o-Ps - o-Ps'$ conversion $\sim \sqrt{N_{\text{coll}}}$.

Has to be taken into account (large systematic uncertainty)

$\rightarrow$ limit on $\epsilon \leq 1.5 \times 10^{-7}$
Search for oPs → invisible decay in a vacuum cavity

- Ps mean free path in a vacuum cavity: 30 mm → 1-2 collision instead of $10^4$
- Cross check: change Ps velocity ~ $N_{\text{coll}}$ Number of signal 2 times smaller without affecting the background!

P. Crivelli et al., JINST 5, P08001 (2010)

Positron beam + Hermetic gamma detector
Low energy positron beam - tagging

C. Vigo, L. Gerchow, L. Liszkay, A. Rubbia, and P. Crivelli


Coincidence with positron bunching and detection of secondary electrons

Flat background from accidental triggers \( \sim 10^{-4} \)
mainly e- from target at HV not correlated with e+
Positron-positronium converter - porous SiO$_2$

Ps mean energy $\sim 1/(e^+ \text{ implantation energy})$

$N_{\text{collisions}} \sim 1/(e^+ \text{ implantation energy})$

$\tau_{\text{oPs, vac}} = 142$ ns

Porous Silica thin film
$\sim 1\mu$m, 3-4 nm pore size

Few keV

Detection of annihilation photons


ECAL: 20X₀ @ 511 keV

- Energy losses and hermeticity <10⁻⁷
- Main limitation: positronium/positron escaping the detection region ≈ 10⁻⁵
**oPs → invisible decay in a vacuum cavity - first results (2018)**

- First results: no excess above expected background observed
  - limit similar to aerogel experiment but without systematic related to collisions.


- Main limitations: accidental triggers, positronium escaping the detection region

**Setup Improvement**

- e⁺ flux improved by 1 order of magnitude (W meshes cryogenic moderator)
- Redesign of vacuum cavity to reduce e⁻ emission due to HV
Time distribution of positrons on target

Time distribution of events compatible with 0-energy
Shape of signal or signal-like background driven by e+ arrival on target
Ps escaping detection region $\sim 1/E_{e^+}$
$\rightarrow$ lowest energy points (sidebands)
$\rightarrow$ estimation irreducible background

Bayes theorem for signal branching ratio

No excess of events for $4.6 \times 10^7$ Ps decays

$BR(o-Ps \rightarrow o-Ps' \rightarrow \text{invisible}) < 4.0 \times 10^{-5}$

Mixing strength $\gamma - \gamma' \quad \epsilon < 5.8 \times 10^{-8}$
Summary and Outlook

- Latest results: no excess above expected background observed → for the first time limit comparable to contraints from cosmology.

- Main limitations: accidental triggers, positronium escaping the detection region

Possible improvements

- Higher $e^+$ flux (Neon moderator) and better energy spread (Ni/W remoderator)
- Implementation of 10-20 nm carbon foil to block Ps escaping the detection region

- GOAL: reach a sensitivity on mixing strength of $\epsilon \sim 10^{-9}$
  (not excluded by cosmology, motivated by BSM theories, cross check DAMA claim….)

![Diagram showing o-Ps: 1) escaping the detection region, 2) decaying inside the ECAL.](image)
Acknowledgments

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