Searching For Dark Photons at Jefferson Lab

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on Behalf of the Heavy Photon Search Collaboration

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What is a “Dark Photon”?  

Consider a theory in which nature contains an additional Abelian gauge symmetry, $U(1)_D$ 


\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{\varepsilon}{2} F_{\gamma,\mu\nu}F'_{\mu\nu} + \frac{1}{4} F'_{\mu\nu}F'_{\mu\nu} + m_{A'}^2 A'^\mu A'_\mu \]

This gives rise to a kinetic mixing term where the photon mixes with a new gauge boson, “dark photon” or $A'$, through interactions of massive fields → induces small coupling to electric charge

The coupling to electric charge allows for $A'$ production through a process analogous to bremsstrahlung
So Why Search for an Dark Photon?

Both PAMELA and Fermi observe an excess in the positron fraction

\[
e^+/(e^+ + e^-) \]

If dark matter annihilates or decays to an \( A' \) it may explain these anomalies

---

May also play a role in the anomalous magnetic moment of the muon

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[Arkani-Hamed et al., Pospelov & Ritz]

[Volansky & Ruderman, Essig, Schuster, Toro]

[hep-ex/0602035]
How to Search for a Dark Photon?


Collider vs. Fixed Target

Fixed target experiments are ideal \( A' \) hunting grounds!

\[
\sigma \sim \frac{\alpha^2 \varepsilon^2}{E_{CM}^2} \sim \mathcal{O}(10 \text{ fb})
\]

\[
\mathcal{O}(ab^{-1}) \text{ per decade}
\]

\[
\sigma \sim \frac{\alpha^3 Z^2 \varepsilon^2}{m^2} \sim \mathcal{O}(10 \text{ pb})
\]

\[
\mathcal{O}(ab^{-1}) \text{ per day}
\]
**A’ Fixed Target Kinematics & Backgrounds**

### Signal

![Signal Diagram](image)

- Heavier product (here A’) takes most of beam energy
- A’ is produced very far forward $\rightarrow E_{A'} = E_{\text{beam}}$
- A’ decay products opening angle, $m_{A'}/E_{\text{beam}}$
- Long lived A’ will have a displaced vertex $\rightarrow$ Help in the reduction of background

### Trident Backgrounds

**Bethe-Heitler**

![Bethe-Heitler Diagram](image)

- Bethe-Heitler cross section is much larger than radiative but is kinematically distinct
- Radiative and A’ signatures are kinematically **identical**
Some Existing A' Constraints

[arXiv:1209.2558]

Colliders

Previous Experiments

Fixed Target

Not enough luminosity (small cross section)

$\sigma \sim \frac{\alpha^3 Z^2 \varepsilon^2}{m^2}$

$A'$ decays in shield

$A'$ mass

$A'$ Decay Lengths

$l_0 \equiv \gamma c \tau \approx \frac{0.8 \text{ cm}}{N_{\text{eff}}} \left( \frac{E_0}{10 \text{ GeV}} \right) \left( \frac{10^{-4}}{\varepsilon} \right)^2 \left( \frac{100 \text{ MeV}}{m_{A'}} \right)^2$

1 μm

1 cm

10 m

[Rounden Essig]
Some Existing A' Constraints

A' Decay Lengths

\[ l_0 \equiv \gamma c \tau \approx \frac{0.8 \text{cm}}{N_{\text{eff}}} \left( \frac{E_0}{10 \text{ GeV}} \right) \left( \frac{10^{-4}}{\varepsilon} \right)^2 \left( \frac{100 \text{ MeV}}{m_{A'}} \right)^2 \]

Not enough luminosity (small cross section)

Sensitivity to these regions will rely on
- Determination of the invariant mass of the A' decay products → Good mass (momentum) resolution
- Distinguishing A' decay vertices as Non-prompt → Good vertex resolution

\[ \sigma \approx \frac{\alpha^3 Z^2 \varepsilon^2}{m^2} \]

[arXiv:1209.2558]

[Rouven Essig]
Some Existing A' Constraints

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[arXiv:1209.2558]

[Not enough luminosity (small cross section)]

Solution

HPS

HPS Decays in shield

Fixed Target

Colliders

Previous Experiments

[Not enough luminosity (small cross section)]

E141

E137

E774

VEPP3

MESA

Dark/Light

HPS test

HPS

A' decays in shield

E774

VEPP3

MESA

Dark/Light

HPS test

HPS

A' decays in shield

A' mass

[Not enough luminosity (small cross section)]

\[ \sigma \sim \frac{\alpha^3 Z^2 \varepsilon^2}{m^2} \]

Not enough luminosity (small cross section)
The HPS Experiment

- The HPS Experiment will make use of a compact large acceptance, **vertex** detector capable of handling high rates

The HPS detector will be split in half in order to avoid the “Wall of Flame” i.e. beam electrons, bremsstrahlung photons, etc.

The HPS detector geometry is quickly evolving! Several improvements/changes are currently being explored …
Simultaneous delivery of electron beams at different energies and intensities to three experimental halls

- $E_{beam} = n \times 1.1 \text{ GeV}, \, n \leq 6$ up to a maximum of 5.5 GeV (until May 2012)

- **Hall A, C:** $I_{beam} < 100 \, \mu\text{A}$, **Hall B:** $I_{beam} < 800 \, \text{nA}$

- Beam delivery is nearly contious: 2 ns bunch structure

- Able to provide small beam spot (<30 $\mu$m) which will help improve vertexing

- Energy upgrade expected to be complete in 2014 $E_{beam} = n \times 2.2 \text{ GeV}, \, n \leq 6$ up to a maximum of 11 GeV (12 GeV for Hall D)

**CEBAF is ideal for this experiment**, however, schedule is not

- Beam is down until 2015 for 12 GeV upgrade

- Aim is to run using first beam with possible commissioning run in late 2014 (**Will make use of existing Test Run detector**).
Silicon Vertex Tracker

D0 RunIIb sensors

- Cut Dimensions (L × W): 100 mm × 40.34 mm
- Active Area (L × W): 98.33 mm × 38.34 mm
- Readout (Sense) Pitch: 60 μm (30 μm)
- # Readout (Sense) Strips: 639 (1277)
- Breakdown Voltage: > 350 V
- Defective Channels: < 1%

APV25 Readout Chip

- # Readout Channels: 128
- Input Pitch: 44 μm
- Shaping Time: 50 ns nom. (adjustable)
- Output Format: multiplexed analog
- Noise Performance: 270 + 36 × C(pF) e−
- Power Consumption: 345 mW

- 40 MHz readout
- Low noise: S/N > 25
- High radiation tolerance
- “Multi-peak” readout
- \( t_0 \) resolution approx. 2 ns

The SVT will be comprise of 106 sensors & hybrids and 530 APV25 ASICs for a total of 67840 Channels

- Thin layers in order to reduce multiple scattering (0.7%\( X_0 \)/layer)
- Bend plane measurements in all layers (for momentum)
- 90 degree stereo will be used for vertexing

Preliminary Design
- Rotating W Target
- Pattern Recognition
- Vertexing

<table>
<thead>
<tr>
<th>Layer</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>z position, from target [cm]</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>50</td>
<td>70</td>
<td>90</td>
</tr>
<tr>
<td>Stereo angle</td>
<td>90°</td>
<td>90°</td>
<td>90°</td>
<td>50 mrad</td>
<td>50 mrad</td>
<td>50 mrad</td>
</tr>
<tr>
<td>Bend Plane Resolution (μm)</td>
<td>≈ 6</td>
<td>≈ 6</td>
<td>≈ 6</td>
<td>≈ 6</td>
<td>≈ 6</td>
<td>≈ 6</td>
</tr>
<tr>
<td>Stereo Resolution (μm)</td>
<td>≈ 6</td>
<td>≈ 6</td>
<td>≈ 6</td>
<td>≈ 120</td>
<td>≈ 120</td>
<td>≈ 120</td>
</tr>
<tr>
<td># Bend Plane Sensors</td>
<td>4</td>
<td>4</td>
<td>6</td>
<td>10</td>
<td>14</td>
<td>18</td>
</tr>
<tr>
<td># Sterep Sensors</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>10</td>
<td>14</td>
<td>18</td>
</tr>
<tr>
<td>Dead Zone [mm]</td>
<td>± 1.5</td>
<td>± 3.0</td>
<td>± 4.5</td>
<td>± 7.5</td>
<td>± 10.5</td>
<td>± 13.5</td>
</tr>
</tbody>
</table>
Trigger – Hybrid Calorimeter

- Hybrid design comprised of 460 existing PbWO4 crystals and 96 lead-glass crystals
- FADC readout at 250 MHz → allows for a narrow trigger window
- FPGA based trigger selection (Two clusters along with some constraints on their energy and geometry) reduces background trigger rate from 3 MHz to 27 kHz
- Trigger and DAQ capable of a rate of > 50 KHz

6.6 GeV, $I_{beam} = 400$ nA, 0.25% $X_0$ target
HPS Reach

Beam = 2.2 GeV @ 200 nA  
Target = 0.125% \(X_0\)

Beam = 6.6 GeV @ 450 nA  
Target = 0.25% \(X_0\)

Assumes 3 months of running at each energy
The HPS Test Run

- The aim was to determine if the occupancies and trigger rates have been well modeled and are manageable, as well as to show if detector performance estimates were reasonable.

- Used a scaled down version of the HPS detector:
  - 5 Si tracker layers with two sensors per layer (1 axial, 1 stereo)
  - Only use the inner crystals of the Ecal
  - The muon chamber was absent
  - Use existing beamline elements

- HPS Test Run was installed on April 19\textsuperscript{th} and successfully ran until the CEBAF shutdown:
  - SVT design was conceived, built and installed in less than 14 months!
  - Scheduling conflict prevented running using electrons → Ran parasitically using a photon beam instead

### Short photon beam run

<table>
<thead>
<tr>
<th>Target thickness (rad. len)</th>
<th># Events</th>
<th>Approx. trigger rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>no target</td>
<td>0.6M</td>
<td>0.3k</td>
</tr>
<tr>
<td>0.18%</td>
<td>2M</td>
<td>0.4k</td>
</tr>
<tr>
<td>0.45%</td>
<td>1M</td>
<td>0.6k</td>
</tr>
<tr>
<td>1.6%</td>
<td>1.5M</td>
<td>1.9k</td>
</tr>
</tbody>
</table>
Test Run Performance

Y-Z view of a track

Analysis of Test Run data is still ongoing
→ Comparison to full simulation is beginning
HPS Collaboration

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(Dated: May 7, 2012)
Backup
Dead Zone chosen such that the occupancy at Layer 1 is approx. 1%

$A^1$ production rate is proportional to the product of the beam current and the target thickness → Prefer to run using a thinner target and higher currents in order to reduce multiple scattering

Acceptance is calculated by requiring the $e^+e^-$ to hit the first five layers

Decay at Target

--- Decay at 10 cm

-- Decay at 20 cm

Dead Zone Limited

Transverse size of SVT Limited
Mass and Vertex Resolution

Dominated by Multiple Scattering

\[ \sigma(Z) = \sqrt{2L} \frac{\delta \theta}{\theta} \]

0 Mishits \( \rightarrow \) \( \frac{\sigma(p)}{p} \approx 1.5\% \)

Bad Hits > 1
Mass and Vertex Resolution

Event selection:
- Track $X^2 < 20$
- $p(A') < E_{\text{beam}}$
- $|V_x| < 400 \mu m$ and $|V_y| < 400 \mu m$
- Cluster isolation in Layer 1 $>500 \mu m$
- Vertex $X^2 < 15$

These cuts have not been optimized.

Tracks with Mishits

Vertex Position of Prompt Decays
## Trigger Rates

<table>
<thead>
<tr>
<th>Trigger Cut.</th>
<th>200 MeV/c² A’ Acceptance</th>
<th>Background Acceptance</th>
<th>Background rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Events with least two opposite clusters</td>
<td>42.35%</td>
<td>2.30%</td>
<td>2.9 MHz</td>
</tr>
<tr>
<td>Cluster energy &gt; 500 MeV and &lt; 5 GeV</td>
<td>44.25%</td>
<td>0.123%</td>
<td>154 kHz</td>
</tr>
<tr>
<td>Energy sum &lt;= E_{beam} * sampling fraction</td>
<td>44.25%</td>
<td>0.066%</td>
<td>82.5 kHz</td>
</tr>
<tr>
<td>Energy difference &lt; 4 GeV</td>
<td>44.20%</td>
<td>0.062%</td>
<td>77.5 kHz</td>
</tr>
<tr>
<td>Lower energy - distance slope cut</td>
<td>43.46%</td>
<td>0.047%</td>
<td>58.8 kHz</td>
</tr>
<tr>
<td>Clusters coplanar to 40°</td>
<td>42.33%</td>
<td>0.0258%</td>
<td>32.3 kHz</td>
</tr>
<tr>
<td>Not counting double triggers</td>
<td>38.58%</td>
<td>0.0210%</td>
<td>26.3 kHz</td>
</tr>
</tbody>
</table>

### Trident Rates after trigger cuts are applied

<table>
<thead>
<tr>
<th>Trident</th>
<th>Estimated trigger rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coherent trident</td>
<td></td>
</tr>
<tr>
<td>Bethe-Heitler</td>
<td>7.8 kHz</td>
</tr>
<tr>
<td>Radiative</td>
<td>130 Hz</td>
</tr>
<tr>
<td>Incoherent trident</td>
<td>180 Hz</td>
</tr>
</tbody>
</table>
Muon Detector

Iron Absorber
30 cm + 3x15 cm

Sci. Hodoscopes
1.5 cm

75 cm