The HPS Experiment: Searching for Dark Photons at Jefferson Lab

Sarah K. Phillips
The University of New Hampshire
on behalf of the HPS Collaboration

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An Aside: Nomenclature

There seem to be many terms for basically the same things:

- Dark Sector = Hidden Sector = Secluded Sector
- Dark Photon = Heavy photon = A' = U-boson = …
- Coupling strength: $\epsilon^2 = k^2 = \chi^2 = \alpha'/\alpha$
If there is an additional $U(1)$ symmetry in nature, there will be mixing between the photon and the new gauge boson.

Holdom, Phys. Lett B166, 1986

$$L_{U(1)'} = -\frac{1}{4} V_{\mu\nu}^2 - \frac{\epsilon}{2} V_{\mu\nu} F_{\mu\nu} + |D_\mu \phi|^2 - V(\phi)$$

- Very general conclusion
- One of the few ways for a new force to communicate with the Standard Model
- Gives coupling of normal charged matter to the new “heavy photon” $q = \epsilon e$
Hints from Astrophysics?

PAMELA, FERMI – energetic e+/e- cosmic rays

- Excess in e+/e- ratio
- But not in the $\bar{p}/\bar{p}$ ratio
- FERMI sees it too!

- Unknown source of high energy positrons...
- From DM annihilation through $A'$?
Dark Photons

- Depending on the model, the mass is in the MeV to GeV range!
- Can mediate dark matter decay and scattering!

DM decays through intermediate A'  
A' mediates DM scattering

- New “dark force” with gauge boson ~ GeV while the dark matter particle (charged under the new force) ~ TeV
- Decays to lepton pairs (e+e−, μ+μ−) but pū decays are kinematically forbidden

N. Arkani-Hamed et al., PRD 79, 015014 (2009)


“Naturalness” arguments and hints from experiments seem to point to the same region in coupling-mass space:

\[
\epsilon \sim 10^{-2} - 10^{-5} \\
\text{m}(A') \sim \text{MeV} - \text{GeV}
\]

A great place for exploration!
How to search for a dark photon?

Wherever there is a normal photon there is a dark photon...

**Collider**

\[
s \sim \frac{\alpha^2 \epsilon^2}{E^2} \sim O(10 \ fb)
\]

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

**Fixed Target**

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

\[O \ ab^{-1} \text{ per day}
\]

But much higher backgrounds!

Fixed Target Searches

Look for radiated A’ decay to $e^+e^-$, $(\mu^+\mu^-)$

**Bump Hunt:**
Look for signal over background

**Bump Hunt + Vertexing:**
Look for signal over background, reduce background with vertexing.

Background Separation

Bethe-Heitler

Radiative

$\sigma_{\text{B-H}}$ very large $\gg \sigma_{\text{Rad}}$.
But kinematically distinct $\rightarrow$
Use clever trigger to separate.
A' Lifetime

\[ \gamma_{\text{cut}} \propto \left( \frac{10^{-4}}{\varepsilon} \right)^2 \left( \frac{100 \text{ MeV}}{m_{A'}} \right)^2 \]

Lower \( \varepsilon \), lower mass = longer lifetime

Background is all prompt → Lower coupling can be reached using vertexing.

[Rouven Essig]
So, How Do We Do This?

This is what is needed:

- Measurement needs to cover the low coupling ($<10^{-4}$), intermediate mass (20-1000 MeV) region
- Low rate, so need intense beam
- High background, so need high resolution and need to measure displaced vertex
The Heavy Photon Search Experiment

The Heavy Photon Search (HPS) is a new experiment in Hall B at Jefferson Laboratory to search for new dark photons in the mass range of 20 MeV/c^2 to 1000 MeV/c^2.

- About 50 members from 16 institutions; both HEP and nuclear physics!
The Heavy Photon Search Experiment

- High rate, high acceptance, high mass & vertex resolution detector to run in JLab Hall B
- JLab PAC37 January 2011 - conditional approval on test run.
- Received DOE funding to build test run apparatus; test run ran in May 2012
CEBAF at Jefferson Lab

JLab: an electron accelerator facility (CEBAF) in Newport News, Virginia

- Simultaneous delivery of beam at different energies and intensities to three experimental halls
  \[ E_{\text{beam}} = n \times 1.1 \text{ GeV}, \ n \leq 5 \ (5.5 \text{ GeV max}) \text{ until May 2012} \]
- Max design current: \( I_{\text{beam}} = 200 \mu\text{A} \) divided among three halls
- 2 ns bunch separation; short integration times reduce ~DC backgrounds
- Energy upgrade (complete 2014)
  \[ E_{\text{beam}} = n \times 2.2 \text{ GeV}, \ n \leq 5 \ (11 \text{ GeV max to ABC, 12 GeV to Hall D}) \]
Beam Quality in Hall B

- Very stable beam
- low halo = low background
- 10 μm spot possible with additional quads; constrains A' trajectory, reducing backgrounds
- Tight beam spot helps tracking & vertex
- $I_{\text{beam}} = 1$ to 500 nA

Beam Tail $< 10^{-5}$

Hall B optics w/ new quads

~10 μm
Hybrid design uses 460 existing PbWO$_4$ crystals, 96 lead-glass crystals (recycled from other experiments!)

Flash-ADC readout at continuous 250 MHz

FPGA based trigger logic: Reduces two cluster background trigger rate from ~4 MHz to ~20 kHz, by using unique A' signature.

Keep high A' acceptance.
Tracker

Requirements:

- Forward angular coverage gives large acceptance (1000x two spectrometers)
- High Rate capable = 25 MHz
- Thin (reduce M.S.)
- Robust, movable, replaceable, operate in vacuum
- Excellent hit resolution
- Cost is acceptable.

Build Using:

- Si Microstrip detectors (106, thin, leftover from Tevatron Run IIb)
- AVP25 readout chip (67840 channels, from CMS, S/N~34, timing ~ 2ns)
- Cooling outside tracking volume. ( ~0.5% $X_0$ per layer)
Tracker Acceptance

- At small A’ mass, dead zone limits acceptance
- At large A’ mass, limited by size of layers 5,6
- Increased z-vertex displacement increases dead zone

Graph showing acceptance as a function of A’ mass for different values of Zv (Zv = 0cm, 10cm, 20cm) with E_{beam} = 5.5 GeV
Tracker Resolution

- Mass resolution dominated by multiple scattering
- Prompt tails to ~ 0 quickly; greater sensitivity further out.

\[ \Delta m/m \sim 1\% \]  
\[ \Delta z \sim 1 - 4 \text{ mm} \]
Muon Detector

- located about 2m from the target
- iron absorbers – 30 cm + 3 × 15cm
- four segmented hodoscopes, 1.5 cm thick
HPS Reach

**Blue:**
- Beam = 2.2 GeV at 200 nA
- Target = 0.125%

**Red:**
- Beam = 6.6 GeV at 450 nA
- Target = 0.25%

3 months of running each energy = 180 days

Solid: $2\sigma$  Dashed: $5\sigma$
Other Experiments

Many experiments in the works to look for Dark Forces!

**APEX** – JLab Hall A & **Mainz A1** ~ same region as APEX; Uses spectrometers.

**DarkLight** – JLab FEL Using H₂ gas target, recoil detector.

Not shown: VEPP-3, BABAR, BELLE, KLOE, BES, SuperB, D0, Atlas, CMS,...
HPS Test Run

- Goal: Test the concept and methods before building full system in a physics environment
- Reduced size tracker and calorimeter (no muon detector)
- Verify background estimates, SVT & Ecal occupancies, trigger algorithm, DAQ performance
- Run before JLab shutdown for 12 GeV upgrade this May; ran parasitically with HDIce experiment in Hall B
SVT and Vacuum Chamber

Tracker and vacuum chamber preparations for the test run.

SVT Module assembly

SVT cosmic tests

Tracker module

Vacuum system
HPS Test Run

• Just finished running on May 18th! Data analysis is in progress...
• Technical challenges were met successfully
• Analysis ongoing to show that trigger rates and tracker occupancies agree with simulations
• Results will be submitted to JLab PAC39 to get approval for full HPS run
In Summary

There has been a lot of interest in the dark sector lately!

- There are compelling reasons to look for the A'
- The Heavy Photon Search at JLab is a challenging experiment looking for dark photons.
- HPS has unique capability to probe intermediate couplings; complimentary to other efforts
- Just completed a successful test run
- Full experiment will run in Jefferson Lab's Hall B after the accelerator comes back up after the upgrade in 2014.

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HPS Simulation

Simulation uses tools developed for lepton collider studies

- GEANT4-based simulation package, “SLIC”
- Signal and trident background events are simulated using MadGraph
- Beam backgrounds generated using GEANT single particle gun
- Java-based digitization and reconstruction, “lcsim,” includes detailed simulation of silicon response; fast, robust track finding; and track/vertex fitting packages: used for ILC, CLIC, ATLAS upgrade and Muon Collider studies.
The HPS Collaboration

About 50 members from 16 institutions.

A. Grillo, V. Fadeyev — University of California, Santa Cruz, CA
M. Ungaro — University of Connecticut, Department of Physics, Storrs, CT
W. Cooper — Fermi National Accelerator Laboratory, Batavia, IL
A. Micherdzinska — The George Washington University, Department of Physics, Washington, DC
G. Ron — Hebrew University of Jerusalem, Jerusalem, Israel
M. Battaglieri, R. De Vita — INFN, Sezione di Genova, 16146 Genova, Italy
M. Holtrop (Co-Spokesperson), K. Slifer, S. K. Phillips — University of New Hampshire, Department of Physics, Durham, NH
M. Khandaker, C. Salgado — Norfolk State University, Department of Physics, Norfolk, VA
S. Bueltmann, L. Weinstein — Old Dominion University, Department of Physics, Norfolk, VA
A. Fradi, B. Guegan, M. Guidal, S. Niccolai, S. Pisano, E. Rauly, P. Rosier and D. Sokhan — Institut de Physique Nucleaire d'Orsay, 91405 Orsay, France
P. Schuster, N. Toro — Perimeter Institute, Ontario, Canada N2L 2Y5
P. Stoler, A. Kubarovsky — Rensselaer Polytechnic Institute, Department of Physics, Troy, NY
K. Griffioen — The College of William and Mary, Department of Physics, Williamsburg, VA
N. Dashyan, N. Gevorgyan, R. Paremuzyan, H. Voskanyan — Yerevan Physics Institute, 375036 Yerevan, Armenia
HPS Test Run ECal