An Overview of Dark Matter Experiments at Jefferson Lab

James R. Boyce on behalf of Collaborations: LIPSS, DarkLight, HPS, and APEX
Jefferson Lab, Newport News, VA 23606, USA
boyce@jlab.org

Abstract. Dark Matter research at Jefferson Lab started in 2006 with the Light Pseudoscalar and Scalar Search (LIPSS) collaboration to check the validity of results reported by the PVLAS collaboration. In the intervening years interest in dark matter laboratory experiments has grown at Jefferson Lab. Current research underway or in planning stages probe various mass regions covering 14 orders of magnitude: from $10^{-6}$ eV to 100 MeV. This presentation will be an overview of our dark matter searches, three of which focus on the hypothesized $A'$ gauge boson.

1. Introduction: Tools of Jefferson Lab: CEBAF and Free-Electron Accelerator (FEL)
The Thomas Jefferson National Accelerator Facility (Jefferson Lab), located in Newport News, VA, uses superconducting RF (SRF) linacs accelerating electrons up to 6 GeV for fixed target experiments in three experiment halls. Details of CEBAF are found elsewhere. An expansion program is currently underway to double the energy to 12 GeV.
The Free-Electron Laser (FEL) facility uses SRF linacs to send a high quality electron beam through a wiggler to generate a photon beam. The photons are captured in an optical cavity that allows a small fraction, < 10%, to be guided with mirrors to experiments conducted in User Laboratories. Figure 1 is a layout of the FEL.
These two accelerator facilities have unique electron and photon beam characteristics for experiments designed to search for Dark Matter (DM) particles in laboratory settings. This overview will focus on two experiments using CEBAF and two using the FEL.

2. Light Pseudoscalar and Scalar Search (LIPSS) [4]
The LIPSS experiment uses the “Light Shining through a Wall” (LSW) technique whereby an intense, linearly polarized laser beam is passed through a strong magnetic field. See figure 2. A coupling of the photons and magnetic field could produce a Light Neutral Boson, $A^0$. The $A^0$ continues in the same direction as the photons - passing through a mirror that deflects the laser beam - and enters into another strong magnetic field where a photon is regenerated from the coupling of the $A^0$ with the magnetic field. These regenerated photons are then detected by a cooled CCD camera. When the light and/or the $A^0$ are in the magnetic field, they are in a vacuum chamber that is pumped down to better than $10^{-6}$ torr. Figure 3 shows the layout of the LSW experiment.
Results of the initial LIPSS experiment have been reported elsewhere. A sample of the results is shown in figure 4 taken from and shows a comparison with other LSW experiments. Such data can be used to set boundaries for scalars, pseudoscalars, Paraphotons, and Millicharged fermions.
Figure 1. Jefferson Lab’s IR/UV FEL Layout. Electrons from the Electron gun (upper right) are injected into the three linac cryomodules, accelerated to maximum energy, travel counter-clockwise around the beam line – either through the IR line or the UV line – and re-injected into the three cryomodules at 180 degrees out of phase, decelerated and deposited in the Recirculating Beam Dump. Laser light - generated when the electrons pass through the wiggler – is captured between two mirrors. A small fraction of the captured light is “out-coupled” from one of the mirrors and is sent to the experimental Labs.

Figure 2. Incident light (g) couples to photons in the magnetic field (B) creating the hypothetical light neutral boson, $A^0$. The weakly interacting $A^0$ passes through the optical barrier (the “wall”) and into the second magnetic field where photons are regenerated from the interaction of the $A^0$ with the second magnetic field. The probability of generating $\gamma$ to $A^0$ is $P_{\gamma \rightarrow A^0}$ where $g$ is coupling constant, $B$=magnet field, $m$ is mass of $A^0$, $L$ = mag field length, and $\omega$ = photon energy.

$$P_{\gamma \rightarrow A^0} = P_{A^0 \rightarrow \gamma} = \frac{(gB)^2}{m^4} \sin^2 \left(\frac{m^2 L}{4\omega}\right)$$
Figure 3. The LIPSS LSW experiment layout. Laser light from the FEL at 935 nm enters from the left, is guided via turning mirrors (TM1 And TM2) into the vacuum chamber GV inside the 1.7 T magnetic field, then exits and is directed by TM3 into a laser beam dump. Any $A_0$ produced travels through the mirror and enter the second vacuum chamber inside the second 1.7 T magnet. Regenerated photons from the conversion of $A_0$’s are collected by the CCD camera.

Figure 4. A sample of the results of LSW experiments as compiled in Reference [8].

3. LIPSS-2 Photon-boson kinetic mixing: next steps.
Paraphotons are bosons generated via kinetic mixing. [7,8] The optical cavity of the FEL has ~ ten times more photons than the out-coupled light. A LSW system in line with the optical cavity could search for these Paraphotons. See Figure 6.

Figure 5. Paraphotons can occur via kinetic mixing as described in [5]. The probability of transmission through an LNS setup is $P_{trans}$, where $\chi$ is the coupling constant, $\omega$ is the photon energy, and $m_{\gamma'}$ is the Paraphoton mass.

$$P_{trans} = 16 \chi^4 \left[ \sin \left( \frac{\Delta k L_1}{2} \right) \sin \left( \frac{\Delta k L_2}{2} \right) \right]^2$$

where $\Delta k = \sqrt{\omega^2 - m_{\gamma'}^2}$
Figure 6. The FEL Optical Cavity contains ~10 times more photons than is available with the “out-coupled” beam. Paraphotons (bosons), generated via kinetic mixing, would exit as shown. A detector system in line with the cavity and with parameters as shown, could extend the explored parameter space, shown in solid blue line, beyond the most recent ALPS results [8], shown in black dashed line. [9]

4. Detecting A Resonance Kinematically with e\textsubscript{Electrons} Incident on a Gaseous Hydrogen Target (DarkLight). [10]

DarkLight is another proposed search for new light bosons using the Jefferson Lab FEL facility. It uses the high current (~ mA), low energy (~130 MeV) electron beam on a diffuse hydrogen gas target. The experiment is based on predictions described in [11]. Figure 7 depicts the interaction whereby an electron scatters off the proton and a light boson, A’, generated near the e-p scattering, subsequently decays into an electron positron pair. The detector system being designed will incorporate a solenoid magnet surrounding the interaction region downstream from the UV wiggler (See figure 2.) Evidence for the hypothesized A’ would consist of a narrow resonance on a large QED background. Also shown in figure 7 is the region of parameter space DarkLight will probe. The expected Luminosity is about 1 ab\textsuperscript{-1}/month.
Figure 7. DarkLight reaction and the parameter space explored by DarkLight. The coupling constant, is $\alpha' / \alpha$, where $\alpha' \equiv \epsilon^2 \alpha$, $(\alpha = e^2 / 4\pi)$. Regions in grey, as well as KLOE, Belle, and KTeV, are regions previous experiments have excluded for the generation of A’s. The two DarkLight curves are for different run times.

5. Heavy Photon Search (HPS). [12]

The HPS Collaboration has proposed an A’ search that would probe two additional regions of parameter space. The HPS would be located downstream from current Hall B equipment. Figures 8 and 9 show the concept and layout. [13]

Figure 8. The HPS experiment’s target and detection system. The electron beam, traveling left to right, strikes a thin target close to compact Si trackers in a 1T dipole. Downstream of the tracker is a fast, segmented electromagnetic calorimeter for triggering and e- identification. There will also be a $\mu$ detector for alternate trigger and $\mu$ identification. The detectors are split vertically to avoid the “Dead Zone” occupied by primary beam, bremsstrahlung photons, etc.
Figure 9. The HPS setup in Hall B. Electrons enter Hall B from the lower right traveling through the CLAS setup and into the HPS setup located between CLAS and the Hall B beam dump. [12, 13].

Figure 10: HPS Reach: Bump Hunt and Vertex Search. These estimates are for a 1 month run @ 400 nA of beam. The bright red is for an e- beam of 5.5 GeV energy and the maroon is for an e- beam of 3.3 GeV. [14]
6. A Prime Experiment (APEX). [15]

The full APEX experiment will be conducted by the APEX Collaboration in Jefferson Lab’s Hall A using both spectrometer arms rotated as close to each other as possible. (Shown in figure 11 is a cartoon with the electron arm rotated away from the Hadron arm.) APEX will probe coupling constants $\alpha'/\alpha \approx 10^{-7}$ and $A'$ mass between $\sim 50$ and $500$ MeV.

![Figure 11. APEX uses the two spectrometers in Hall A. On the left is a graphic of the spectrometers with the electron arm rotated away from the beam line and the Hadron arm. On the right is a sketch of the APEX setup where both spectrometers are $\pm 5^\circ$ from the beam line. A septum magnet is inserted between the W target to provide the separation needed between positrons and electrons for the High Resolution Spectrometers. This arrangement allows for excellent mass resolution, it dramatically suppresses large background from elastic scattered electrons and Moller electrons. The setup also suppresses background from $\gamma \rightarrow e^+ e^-$ and radiated $\gamma \rightarrow e^+ e^-$.](image)

In July 2010 a Test Run of APEX was conducted to answer specific questions about the feasibility of the full APEX run as proposed by the Collaboration. [16] The Test Run successfully obtained results comparable to results reported in reference [17] and shown in figure 12.

![Figure 12. The full APEX experiment will probe the region of parameter space shown in purple on the left. On the right is the expanded region showing the results of the APEX Test Run [16] compared to the results reported by MAMI [17].](image)
7. Conclusions
In recent years, starting with LIPSS, interest in Dark Matter experiments at Jefferson Lab has increased due to the realization that the tools – accelerators and experimental Halls – are ideally suited for Intensity Frontier explorations. This Overview has described several Dark Matter experiments recently conducted or proposed using these facilities. LIPSS successfully conducted and published use of the FEL for probing parameter space for pseudoscalars, scalars, Paraphotons, and millicharged fermions in the mass region from $10^{-6}$ to $10^{-3}$ eV. DarkLight proposes to search for a new vector gauge boson, A’, using the electron beam of the FEL scattering off a hydrogen gas target. APEX and HPS also propose searches for the A’ using Jefferson Lab’s Hall A and Hall B respectively. APEX has successfully completed and published a test run. Setup for both DarkLight and HPS are in progress. Thus Jefferson Lab is poised to venture into unexplored regions of dark matter parameter space.

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