DarkLight: A Search for Dark Forces at the Jefferson Laboratory Free-Electron Laser Facility

Contributed to the Community Summer Study 2013
"Snowmass on the Mississippi"
University of Minnesota
Minneapolis, Minnesota USA

29 July–6 August 2013

J. Balewski, J. Bernauer, W. Bertozzi, J. Bessuille, B. Buck, R. Cowan, K. Dow, C. Epstein, P. Fisher, S. Gilad, E. Ihloff, Y. Kahn, A. Kelleher, J. Kelsey, R. Milner, C. Moran, L. Ou, R. Russell, B. Schmookler, J. Thaler, C. Tschalär, C. Vidal, A. Winnebeck
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA 02139, USA and the Bates Research and Engineering Center, Middleton MA 01949 USA

S. Benson, C. Gould, G. Biallas, J. R. Boyce, J. Coleman, D. Douglas, R. Ent, P. Evtushenko, H. C. Fenker, J. Gubeli, F. Hannon, J. Huang, K. Jordan, R. Legg, M. Marchlik, W. Moore, G. Neil, M. Shinn, C. Tennant, R. Walker, G. Williams, S. Zhang *Jefferson Lab, 12000 Jefferson Avenue, Newport News, VA 23606 USA*

M. Freytsis
Physics Dept. U.C. Berkeley, Berkeley, CA 94720 USA

R. Fiorito, P. O'Shea
Institute for Research in Electronics and Applied Physics University of Maryland, College Park, MD 20742 USA

R. Alarcon, R. Dipert
Physics Department, Arizona State University, Tempe, AZ 85004 USA

G. Ovanesyan
Los Alamos National Laboratory, Los Alamos NM 87544 USA

T. Gunter, N. Kalantarians, M. Kohl
Physics Dept., Hampton University, Hampton, VA 23668 and Jefferson Lab, 12000 Jefferson Avenue, Newport News, VA 23606

USA

I. Albayrak, M. Carmignotto, T. Horn
Physics Dept., Catholic University of America, Washington, DC 20064 USA

D. S. Gunarathne, C. J. Martoff, D. L. Olvitt, B. Surrow, X. Lia
Temple University, Philadelphia PA 19122 USA

R. Beck, R. Schmitz, D. Walther
University Bonn, D-53115 Bonn Germany

K. Brinkmann, H. Zaunig
Physikalisches Institut Justus-Liebig-Universitt Giessen, D-35392 Giessen Germany

Abstract

We give a short overview of the DarkLight detector concept which is designed to search for a heavy photon A' with a mass in the range 10 MeV/$c^2 < m_{A'} <$ 90 MeV/c^2 and which decays to lepton pairs. We describe the intended operating environment, the Jefferson Laboratory free electon laser, and a way to extend DarkLight's reach using $A' \rightarrow$ invisible decays.

1 Introduction

The DarkLight detector is a compact, magnetic spectrometer designed to search for decays to lepton pairs of a heavy photon A' in the mass range 10 MeV/$c^2 < m_{A'} <$ 90 MeV/c^2 at coupling strengths of $10^{-9} < \alpha' < 10^{-6}$ where $\alpha' = \epsilon^2 \alpha_{EM}$ (see Fig. 1 [left]). The process

$$e^- + p \rightarrow e^- + p + A' \rightarrow e^- + p + e^- + e^+$$

will be used to search for a resonance in $m_{A'}$. The reach of the experiment in the (α', $m_{A'}$) parameter space complements that of other existing or proposed heavy photon search experiments. Motivation for searching for an A' in this mass range is discussed in detail elsewhere (see, *e.g.*, section 6.2.2 of Ref. [1]). Here we note that this region is particularly interesting since it includes much of the preferred region for the $(g-2)_\mu$ anomaly. The reach can be extended in α' via inclusion of $A' \rightarrow$ invisible decays by adding photon detection capability. DarkLight will be able to make other measurements as well, such as a measurement of the proton charge radius.

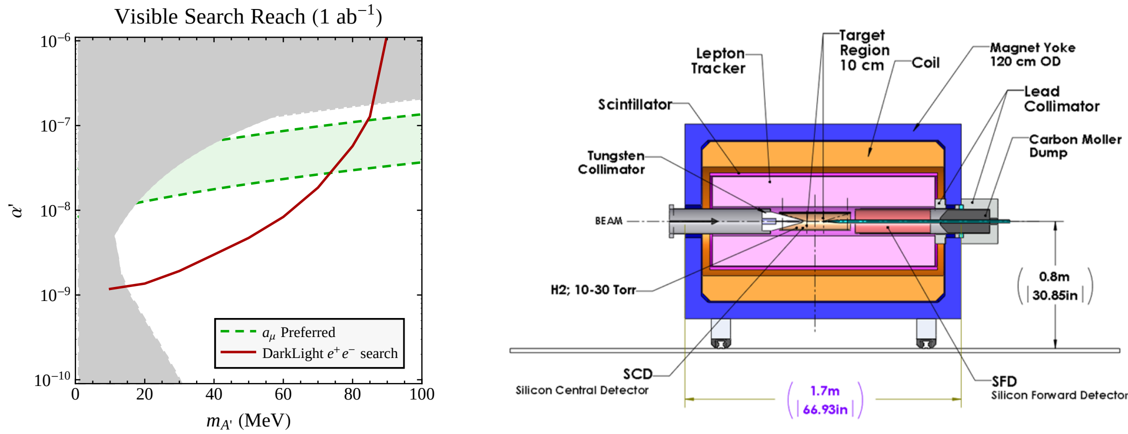

Figure 1: Left: A subset of the A' parameter space of interest to DarkLight. The shaded area is the sum of regions excluded by existing bounds on the electron magnetic moment a_e and the muon magnetic moment a_μ, and by beam dump experiments. The curve shows the expected reach for DarkLight. The dotted region is the a_μ preferred region. Observation of an A' in this region could explain the known $(g-2)_\mu$ anomaly. Right: Schematic cross-sectional view of the DarkLight detector identifying its main components.

The experiment reconstructs the 4-vectors of all visible final-state particles; for an A' decaying to e^+e^-, one can use the reconstructed invariant mass spectrum of electron/positron pairs to search for the narrow ($\approx$ 1 MeV/c^2) A' mass peak, while the 4-vectors of the remaining particles provide checks on the kinematics and background suppression. The key to detection is adequate control of the irreducible QED background, which requires excellent momentum resolution for the leptons and excellent energy resolution for the proton.

2 Experimental Setup

DarkLight is designed for operation at the 100 MeV JLab Free Electron Laser (FEL) facility. The FEL electron beam will be directed onto a windowless, dense (10^{19}/cm^2) hydrogen gas target located in a 0.5 T solenoidal magnetic field (see Fig. 1 [right]). Surrounding the target are two double-layer, central and forward silicon detectors for detection of the recoil proton and for lepton tracking. These are located inside the beampipe and cover the polar angular range $5° - 90°$. Outside the beampipe is a lepton tracker covering angles $25° - 165°$. A lead scintillator sandwich for photon detection surrounds the tracker. Other components include a tungsten collimator inside the beampipe to remove elastically scattered, high-p_T electrons, a Møller dump, and a lead shield to prevent backscattered radiation originating in the Møller dump from entering the tracker. All components except the dump are located inside the magnet and iron yoke.

2.1 Jefferson Laboratory Free Electron Laser Facility

DarkLight is expected to be installed on the UV beamline at the JLab FEL at location A1 as shown in Fig. 2. The FEL provides a beam power of up to 1 MW (10 mA current). Using the dense hydrogen target described above, it will provide 1 ab^{-1} of integrated luminosity per month of operation.

2.1.1 Transmission Tests

A series of beam tests in summer 2012 verified that sustained, high-power transmission of the FEL beam through millimiter-size apertures is feasible [2]. These tests culminated in a 7-hour-long run with a 430 kW beam directed through a 2 mm diameter, 127 mm long aperture in an aluminum block where beam losses of less than 3 ppm from halo interception and wakefield effects were achieved [3]. Radiation backgrounds were measured and found to be acceptable and in agreement with FLUKA and MCNP simulations [4]. Numerous lessons were learned about the sustained operation of the FEL at megawatt power levels [5].

3 Invisibles Search

As mentioned above, the reach of the experiment can be extended by including $A' \to$ invisible decays through adding photon detection capability. The reach for the invisible search for various photon detection efficiencies is shown in Fig. 3. The efficiency refers only to the detection efficiency *within* the detector volume; photons which escape the lepton tracking region are not detected. We see that with 95% photon detection efficiency, we can probe the majority of the preferred region. With no photon detection, the invisible search does not even extend to a region of parameter space which is not already excluded by anomalous magnetic moment data. Even with 50% photon efficiency, we can barely probe the preferred region, thus showing the importance of efficient photon detection. Because photons are primarily

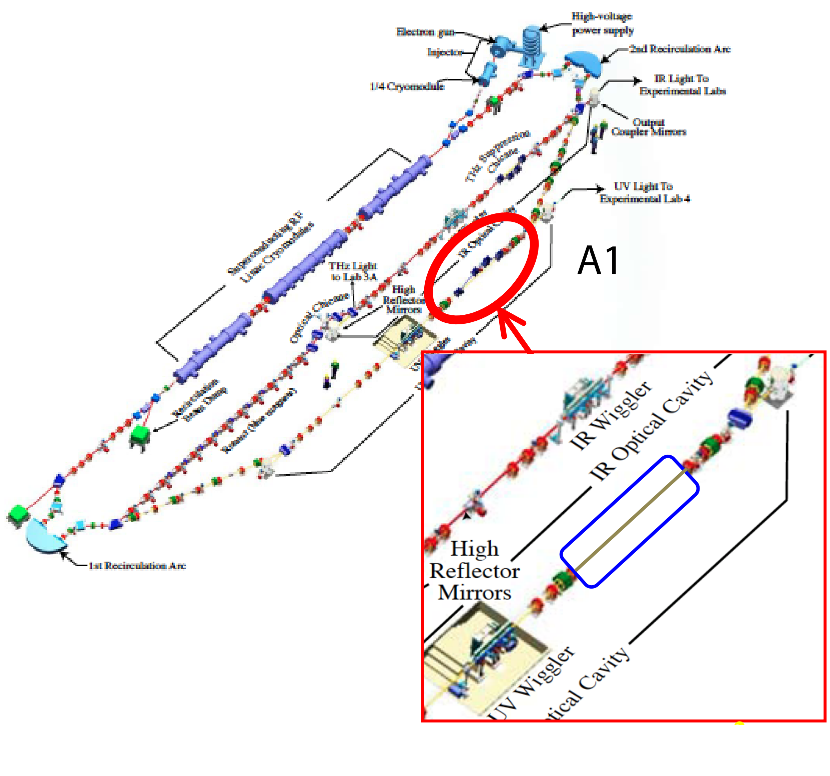

Figure 2: Layout of the JLab FEL. DarkLight will be located at position marked A1 on the UV beamline.

produced collinear with charged particles, a significant fraction of photons will escape down the beamline undetected, limiting the reach in the low invariant mass region.

3.1 Extending the Detector Concept for Invisible Decays

Extending this capability to the DarkLight detector concept could be accomplished by adding a lead(Pb)-scintillator sandwich in a cylindrical configuration outside the lepton tracker with approximate dimensions of 60 cm (diameter) x 150 cm (length). The design concept borrows from experience gained with neutrino experiments, including MINERVA and MINOS. For photons of energy 10–100 MeV the cross-section in Pb is around 20 barns. This is below the critical energy, so this would correspond to a single elec-

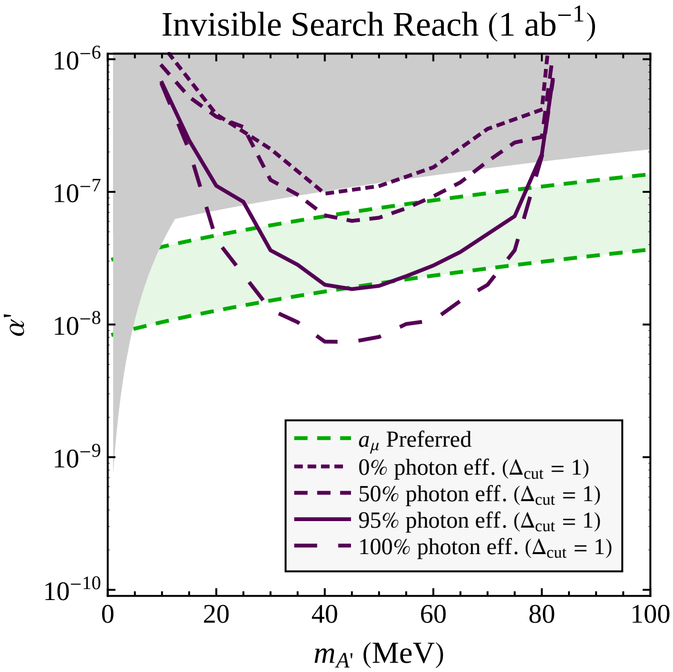

Figure 3: DarkLight invisible search reach for various photon efficiencies. The gray shaded area indicates constraints from anomalous magnetic moment measurements, with the green region indicating the "welcome" region where an A' could explain the $(g-2)_\mu$ discrepancy. $\Delta_{\text{cut}} = 1$ refers to a kinematic cut designed to mitigate mis-measurement of the reconstructed A' invariant mass. Some existing constraints from beam dump experiments are not included in the figure.

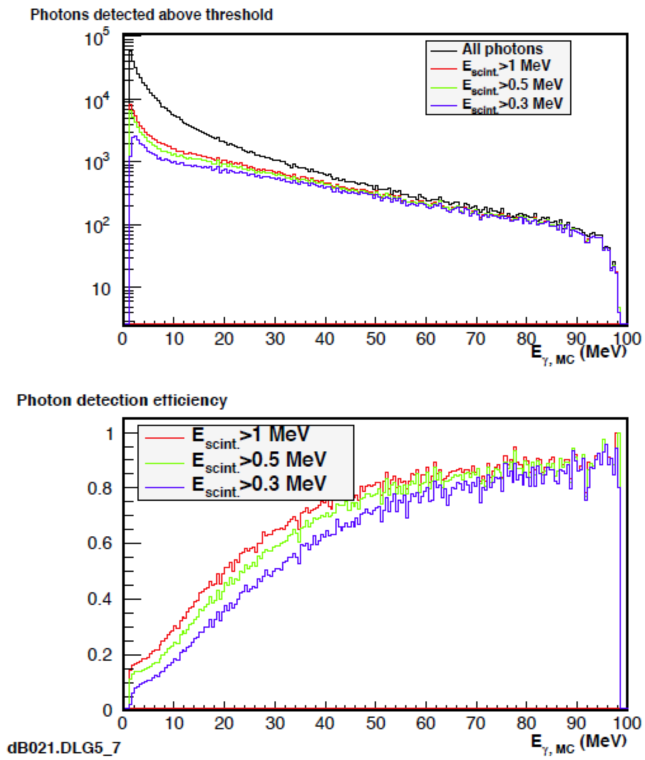

Figure 4: Simulated detection capabilities of 3-layer Pb-scintillator detector concept.

tron with corresponding energy of $E_\gamma/2$ or detection. With the density of Pb being 11.3 g/cm^2 and N = 200 g/mole, this gives a corresponding wavelength $\lambda = 0.7$ cm. Therefore, with lead and scintillator bars of thickness 0.5 cm and 1 cm, respectively, the intrinsic probability per layer would be about 0.53. So for 3 layers the probability of detecting these photons would be approximately 90%. Simulating $ep \to ep\gamma$ is shown in Fig. 4. Studies are underway to optimize the efficiency via prototyping. Optimal read-out setup and energy loss calculations are in progress.

4 Status and Schedule

A proposal was submitted to JLab PAC37 in Jan. 2011 requesting conditional approval to allow us to carry out beam tests at the FEL to ensure our target was compatible with the FEL beam and carry out beam halo measurements. Conditional approval was granted and JLab allocated funds for the beam test, which was successfully completed in July 2012. A final proposal requesting full approval from the Laboratory was prepared for JLab PAC39 [7] which met in June 2012. Approval of DarkLight was granted by JLab in June 2013, and the experiment is moving on to a full technical design. The goal is to commission the detector in 2015 with data-taking in 2016.

References

[1] J. Hewett *et al.*, *Fundamental Physics at the Intensity Frontier*, arXiv:1205.2671, SLAC-R-992, ANL-HEP-TR-12-25, May 2012.

[2] R. Alarcon *et al.*, *Transmission of Megawatt Relativistic Electron Beams Through Millimeter Apertures*, arXiv:1305.0199 [physics.acc-ph], May 2013, submitted to *Phys.Rev.Lett.*.

[3] C. Tschalär *et al.*, *Transmission of High-Power Electron Beams Through Small Apertures*, arXiv:1305.7493 [physics.acc-ph], May 2013, accepted for publication in . *Nucl.Inst.Meth., Section A*.

[4] R. Alarcon *et al.*, *Measured Radiation and Background Levels During Transmission of Megawatt Electron Beams Through Millimeter Apertures*, arXiv:1305.7215 [physics.acc-ph], May 2013, accepted for publication in *Nucl.Inst.Meth., Section A*.

[5] D. Douglas *et al.*, *Accelerator Operations for DarkLight Aperture Test*, May 2013, JLAB-TN-13-020.

[6] Y. Kahn and J. Thaler, *Searching for an invisible A' vector boson with DarkLight*, Phys. Rev. D **86**, 115012 (2012).

[7] J. Balewski *et al.*, *A Proposal for the DarkLight Experiment at the Jefferson Laboratory Free Electron Laser*, `http://dmtpc.mit.edu/DarkLight/DarkLightProposal_PAC39.pdf`.