Snowmass2021 - Letter of Interest

Shining light through the wall with ALPS II

Thematic Areas:

☐ (CF1) Dark Matter: Particle Like
■ (CF2) Dark Matter: Wavelike
☐ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
☐ (CF7) Cosmic Probes of Fundamental Physics
☐ (Other) *[Please specify frontier/topical group]*

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Abstract:

The Any Light Particle Search II (ALPS II) is an experiment currently being built at DESY in Hamburg, Germany, that will use a light-shining-through-a-wall (LSW) approach to search for axion-like particles. ALPS II represents a significant step forward for these types of experiments as it will use 24 superconducting dipole magnets, along with dual high-finesse, 122 m long optical cavities. The experiment will be the first implementation recipe of the idea, proposed over 30 years ago, to use optical cavities before and after the wall to increase the power of the regenerated photon signal. This concept will allow the experiment to achieve a sensitivity in terms of the coupling between axion-like particles and photons down to $g_{a\gamma\gamma} = 2 \times 10^{-11}$ GeV^{-1} for masses below 0.1 meV, more than three orders of magnitude beyond the sensitivity of previous laboratory experiments.

The axion [1, 2] has been of interest since the late 1970's when the Peccei-Quinn mechanism was first proposed as a solution to the strong CP problem in quantum chromodynamics (QCD) [3]. This solution promotes the QCD θ parameter to a dynamical field, leading to the existence of a new particle, known as the axion. Axion searches employ the Sikivie process, where an external magnetic field stimulates axions and photons to couple to one another due to the following term in the QCD Lagrangian [4]:

$$\mathcal{L} = g_{a\gamma\gamma}\phi_a \vec{E} \cdot \vec{B} \tag{1}$$

where $g_{a\gamma\gamma}$ is the coupling of the axion to two photons, ϕ_a is the axion field, $\vec{E}$ is the oscillating electric field, and $\vec{B}$ represents the static magnetic field. All axion searches take advantage of this effect; their designs are largely dependent on the source of axions that they use. Axions have proven to be an elusive target for experimental physicists and astronomers largely because the coupling $g_{a\gamma\gamma}$ is extremely weak [5, 6].

These particles could explain a number of astrophysical phenomena such as the existence of dark matter [7], the transparency of the universe for highly energetic photons [8], and anomalies in stellar cooling rates [9]. In addition there could be a whole new class of axion-like particles with similar characteristics, such as a low mass and weak interactions with the standard model particles[10–12].

The three primary experiments currently being used to search for axions and axion-like particles are haloscopes, helioscopes, and light-shining-through-a-wall (LSW) experiments. Haloscopes such as ADMX, HAYSTAC and proposed MADMAX [13–15] look for axions that reside in the dark matter galactic halo by using microwave resonators immersed in a magnetic field. Helioscopes (CAST) and the future IAXO experiment [16, 17] use the sun as a source of axions that are subsequently converted to photons by magnetic fields within x-ray telescopes.

LSW experiments take place entirely in the laboratory using a high power laser propagating through a magnetic field. Laser photons convert to a beam of axions or axion-like particles that travel unimpeded through a wall which blocks the laser light [18–22]. A second magnetic field behind the wall will cause some of these axion-like particles to reconvert back to photons which can then be detected. Of the three types of axion searches mentioned so far, the LSW experiments are the least model dependent, but also have so far the weakest sensitivity for the QCD axion. Examples of previous LSW experiments include ALPS I [23] and OSQAR [24, 25]. The Any Light Particle Search II (ALPS II) [26–28] will soon become the world's leading LSW experiment. It will improve on the sensitivity of these earlier experiments by three orders of magnitude and surpass CAST if expressed as an upper limit of the coupling strength between photons and the QCD axion.

In addition to the QCD axion, other "axion-like" particles that can also be described by Eq. 1 have recently taken centerstage. These particles, with potentially stronger interactions, offer explanations for a variety of astrophysical phenomena including the transparency of the universe to highly energetic photons [8] and anomalies in stellar cooling rates [9]. As ALPS II will directly probe the existence of pseudo-scalar fields whose coupling to electromagnetic fields is described by Eq. 1, it will provide new insight into their potential existence independent of dark matter or solar models.

ALPS II will also be able to search for scalar fields whose coupling to electro-magnetic fields can be described by the Lagrangian

$$\mathcal{L} = g_{a\gamma\gamma}\phi_a (E^2 - B^2) \tag{2}$$

Experimentally, this only requires that the polarization of the E-field is orthogonal to the B-field. A signal running in both polarization modes with no observed polarization dependence on the production rate could be detected as well. This may indicate the existence of other types of weakly interacting sub-eV particles (WISPs) that are produced by kinetic mixing such as millicharged particles or hidden sector photons which do not require a static magnetic field to interact with photons [29].

A fundamental advantage of LSW experiments such as ALPS II is that they make no assumptions about the prevalence of any of these particles, but merely probe the interactions themselves without the need for any external sources. LSW experiments can therefore determine the photon-coupling strength independent of any astrophysical assumptions. LSW experiments take place entirely in the laboratory using a high-power laser (HPL) propagating through a magnetic field. This generates a beam of axion-like particles that travel through a light-tight wall into a second magnetic field region where some of these axion-like particles convert back to photons [18].

ALPS II is located at DESY in Hamburg, Germany, taking advantage of the tunnels, magnets, and cryogenic infrastructure formerly used by the HERA accelerator. It will use 122 m long cavities to enhance resonantly the electromagnetic field on both sides of the wall, increasing the photon regeneration rate by twelve orders of magnitude over earlier LSW experiments [23–25]. The entire optical setup including these two cavities has to be tightly controlled to maintain and accurately calibrate the coupling of the generated axion field to the cavities.

The circulating fields in the cavities will propagate through strings of 12 straightened superconducting HERA dipole magnets [30], as shown in Fig. 1. Each 8.8 m long dipole produces a magnetic field of 5.3 T giving a magnetic field times length of B_0L = 560 T·m on each side of the wall with free apertures between 46 and 51 mm. Inside the production cavity (PC) on the left side of the wall, photons will generate relativistic axion-like particles with an identical energy and spatial mode. These particles pass through the light-tight barrier on the central optical bench (COB) before they enter the regeneration cavity (RC) where they convert back to photons.

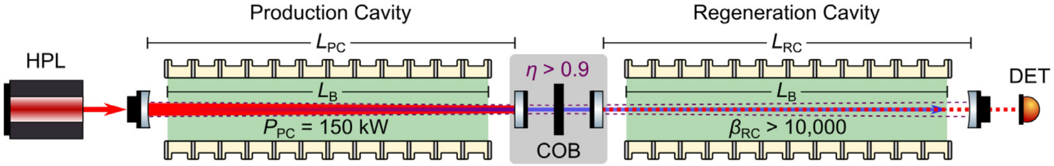

Fig. 1. Experimental layout of ALPS II. Two 106 m long strings of twelve 5.3 T HERA dipoles are separated by the COB. This is where the wall which blocks the PC transmitted light from reaching the RC is housed. Each of the cavities are 122m long. The power inside the PC should be at least 150 kW during the first science runs and the resonant enhancement of the RC must be $> 10,000$. The coupling efficiency between the PC and RC, given by η, should be at least 0.9.

The resonant regeneration experiment delivers power P_r from the regeneration cavity:

$$P_r = \frac{\mathcal{F}_p\mathcal{F}_r}{16\pi^2}(B_0L)_p^2(B_0L)_r^2\eta^2 g_{a\gamma\gamma}^4 P_p, \tag{\textit{Power}}$$

where the subscript p stands for "production cavity," r for "regeneration cavity," $\mathcal{F}$ is the cavity finesse, B_0L is the product of the magnetic field strength and magnetic field string length, η specifies the deviation from perfect overlap of the modes in the two cavities, $g_{a\gamma\gamma}$ is the coupling of the axion to two photons, and P_p is the power sent to the production cavity. The target sensitivity is $g_{a\gamma\gamma} = 2\times10^{-11}$ GeV^{-1} [27, 28].

The ALPS II experiment is under construction, with four magnets installed, clean rooms being commissioned, and many components either purchased or built. The first science run will start in 2021. Two detection schemes will be employed: (1) a heterodyne readout of the regenerated photons, using technology from LIGO and LISA, and (2) transition-edge sensors (TES), using superconducting thin films capable of responding to single photons.

Future plans for the ALPS magnet string include measurements of vacuum birefringence [32, 33] or high frequency gravitational wave searches [34]. Also plans for building larger aperture and stronger dipole magnets with the option to alternate the direction of the magnet fields [21] to significantly improve the sensitivity and mass range of a future axion-like particle searches are currently being developed.

References

[1] S. Weinberg, “A New Light Boson?.” Phys. Rev. Lett. 40 275 (1978).

[2] F. Wilczek, “Problem of Strong P and T Invariance in the Presence of Instantons.” Phys. Rev. Lett. 40 279 (1978)

[3] R. Peccei, and H. Quinn, “CP Conservation in the Presence of Instantons.” Phys. Rev. Lett. 38, 1440 (1977)

[4] P. Sikivie, “Experimental tests of the ‘invisible’ axion.” Phys. Rev. Lett. 51 1415 (1983)

[5] C. Patrignani et al. “Review of Particle Physics.” Chin Phys C. 40, 100001 (2016) (Particle Data Group).

[6] I. Irastorza and J. Redondo, “New experimental approaches in the search for axion-like particles.” Progress in Particle and Nuclear Physics 102, 89 (2018)

[7] M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018) and 2019 update.

[8] M. Meyer et al. “First lower limits on the photon-axion-like particle coupling from very high energy gamma-ray observations,” Phys Rev D. 5, 035027 (2013)

[9] M. Giannotti et al. “Cool WISPs for stellar cooling excesses.” J Cosmol Astrop Phys. 5, 57 (2016)

[10] A. Arvanitaki, S. Dimopoulos, S. Dubovsky, N. Kaloper and J. March-Russell, Phys. Rev. D 81, 123530 (2010)

[11] M. Cicoli, M. Goodsell and A. Ringwald, JHEP 1210, 146 (2012)

[12] J. Halverson, C. Long, B. Nelson and G. Salinas, Phys. Rev. D 100 106010, (2019)

[13] N. Du et al. “Search for Invisible Axion Dark Matter with the Axion Dark Matter Experiment.” Phys. Rev. Lett. 120, 151301 (2018)

[14] L. Zhong et al., [HAYSTAC Collaboration], Phys. Rev. D 97(9), 092001 (2018)

[15] P. Brun et al. “A new experimental approach to probe QCD axion dark matter in the mass range above 40 μeV.” The European Physical Journal C 79, 186 (2019)

[16] V. Anastassopoulos et al. “New CAST limit on the axion-photon interaction.” Nature Physics 13, 584 (2017)

[17] E. Armengaud et al. “Conceptual design of the international axion observatory (IAXO).” Journal of Instrumentation 95, T05002 (2014)

[18] K. Van Bibber et al. “Proposed experiment to produce and detect light pseudoscalars.” Phys. Rev. Lett. 59, 759 (1987)

[19] F. Hoogeveen and T. Ziegenhagen, “Production and detection of light bosons using optical resonators.” Nucl. Phys. B 358, 3 (1991)

[20] Y. Fukuda et al. “Production and detection of axions by using optical resonators.” Prog. Cryst. Growth Charact. Mater. 33 (1996)

[21] P. Sikivie, Tanner D.B., van Bibber K. “Resonantly enhanced axion-photon regeneration.” Phys. Rev. Lett. 98, 172002 (2007)

[22] J. Redondo and A. Ringwald, “Light shining through walls.” Contemp. Phys. 52, 211 (2011

[23] K. Ehret et al. “New ALPS results o n hidden-sector lightweights.” Physics Letters B 689, 149 (2010)

[24] M. Sulc et al. “Axion search by laser-based experiment OSQAR.” Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 718, 530 (2013)

[25] R. Ballou et al. “New exclusion limits on scalar and pseudoscalar axionlike particles from light shining through a wall,.” Phys. Rev. D92, 9, 092002 (2015),

[26] R. Bähre et al., “Any light particle search II – Technical Design Report.” DESY Report 13-030, arXiv:1302.5647 (2013)

[27] M. Diaz et al., “Design of the ALPS II Optical System”, In preparation

[28] A. Hallal et al., ‘Design of the Heterodyne Detection System for ALPS II.” In preparation.

[29] H. Gies, J. Jaeckel, and A. Ringwald. “Polarized light propagating in a magnetic field as a probe for millicharged fermions.” Phys. Rev. Lett. 97.14 140402 (2006)

[30] C. Albrecht et al. “Straightening of Superconducting HERA Dipoles for the Any-Light-Particle-Search Experiment ALPS II”, arXiv:2004.13441, DESY Report 20-070

[31] P. Arias et al. “Optimizing light-shining-through-a-wall experiments for axion and other weakly interacting slim particle searches.” Phys. Rev. D 82, 115018 (2010)

[32] M. Hartman et al. “Characterization of the Vacuum Birefringence Polarimeter at BMV: Dynamical Cavity Mirror Birefringence, ” arXiv:1812.10409

[33] A. Ejlli et al. “The PVLAS experiment: A 25 year effort to measure vacuum magnetic birefringence”, Physics Reports Volume 871, 2 August 2020, Pages 1-74

[34] A. Ejlli et al. “Upper limits on the amplitude of ultra-high-frequency gravitational waves from graviton to photon conversion”, Eur. Phys. J. C (2019) 79: 1032

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