Snowmass2021 - Letter of Interest

# Search for Axion-Like Particles at the Next Generation Neutrino Experiments

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**NF Topical Groups:** (check all that apply ☐/■)
☐ (NF1) Neutrino oscillations
☐ (NF2) Sterile neutrinos
■ (NF3) Beyond the Standard Model
☐ (NF4) Neutrinos from natural sources
☐ (NF5) Neutrino properties
☐ (NF6) Neutrino cross sections
☐ (NF7) Applications
☐ (TF11) Theory of neutrino physics
☐ (NF9) Artificial neutrino sources
☐ (NF10) Neutrino detectors

**RF Topical Groups:** (check all that apply ☐/■)
☐ (RF1) Weak decays of b and c quarks
☐ (RF2) Weak decays of strange and light quarks
☐ (RF3) Fundamental Physics in Small Experiments
☐ (RF4) Baryon and Lepton Number Violating Processes
☐ (RF5) Charged Lepton Flavor Violation (electrons, muons and taus)
■ (RF6) Dark Sector Studies at High Intensities
☐ (RF7) Hadron Spectroscopy

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**Introduction:** Due to the ability to address the strong CP problem [1–3] and to serve as a dark-matter candidate (e.g., Refs. [4–6]), axions are a well-motivated and extensively explored extension of the Standard Model (SM). Theoretical studies (e.g., Ref. [7]) not only investigate the original QCD axion but also have extended to incorporate general axion-like particles (ALPs) in a wide range of models.

An extensive array of approaches are investigating ALPs by exploiting their coupling with photons, electrons, and nucleons which include helioscopes: CAST [8–10], haloscopes: Abracadabra [11, 12], ADMX [13, 14], CASPEr [15], HAYSTAC [16, 17], light-shining-through-walls: ALPSII [18], interferometry [19, 20]: ADBC [21], DANCE [22], current and proposed beam dump and fixed target experiments: FASER [23], LDMX [24, 25], NA62 [26], SeaQuest [27], SHiP [28], hybrids of beam dump and helioscope approaches: PASSAT [29], reactor experiments: MINER, CONUS etc. [30], dark matter experiments: XENON [31, 32], SuperCDMS [33], PandaX [34] etc.

In this Letter of Interest, we propose to investigate axion-photon and axion-electron couplings at neutrino experiments where a high energy particle (proton or electron) beam impinges on a target. These experiments not only produce neutrinos but also photons with high intensity. Our proposal is to use these photons to create ALPs via the Primakoff (and/or Compton-like) processes which would then travel to nearby detectors and would be detected via decay or scattering induced by the inverse Primakoff or Compton-like processes. The main idea behind this LOI is to utilize detectors in the next generation neutrino experiments, such as the near detectors at DUNE, Hyper-K (T2HK/T2HKK) and SBN to detect ALPs produced from the photons at these and future facilities.

**ALP search strategy:** In order to investigate the ALP parameter space, we will focus on a generic model where the ALP can couple to either a photon or an electron as described by interaction terms in the Lagrangian of the form $\mathcal{L}_{\text{int}} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} - g_{aee} a \bar{\psi}_e \gamma_5 \psi_e$ where $a$ denotes the ALP field and where $F_{\mu\nu}$ is the electromagnetic field strength tensor and its dual $\tilde{F}^{\mu\nu} = \epsilon^{\mu\nu\rho\sigma} F_{\rho\sigma}$. Due to the photon coupling, ALPs can be produced through the Primakoff process $\gamma(p_1) + A(p_2) \to a(k_1) + A(k_2)$ [35], where $A$ is an atomic target. This interaction is governed by the strength of the coupling $g_{a\gamma\gamma}$ and is enhanced by the coherency factor $Z^2$ where $Z$ is the atomic number. The forward scattering differential cross-section is [36, 37]

$$\frac{d\sigma_P}{d\cos\theta} = \frac{1}{4} g_{a\gamma\gamma}^2 \alpha Z^2 F^2(t) \frac{|\vec{p}_a|^4 \sin^2\theta}{t^2} \tag{1}$$

Here $\alpha = e^2/(4\pi)$ is the standard electromagnetic fine structure constant, $F^2(t)$ contains the atomic and nuclear form factors, and $|\vec{p}_a|$ is the magnitude of the outgoing three-momentum of the ALP at angle $\theta$ relative to the incident photon momentum. The square of the four-momentum transfer is given by $t = (p_1 - k_1)^2 = m_a^2 - 2E_\gamma(E_a - |\vec{p}_a| \cos\theta)$ for a photon of incident energy $E_\gamma$ that produces an ALP of energy $E_a$ and mass $m_a$.

Within the framework adopted here, once produced, the ALP can generate a detectable signal in several ways. The ALP could decay to two photons or an electron-positron pair with the well-known decay widths

$$\Gamma(a \to \gamma\gamma) = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}\,, \quad \Gamma(a \to e^+e^-) = \frac{g_{aee}^2 m_a}{8\pi} \sqrt{1 - \frac{4m_e^2}{m_a^2}} \tag{2}$$

which, in conjunction with the ALP energy, fix the decay length. Secondly, the ALP could be detected through the inverse Primakoff process $a + A \to \gamma + A$, which has the same differential cross-section as in Eq. (1), with the alteration that the front-factor 1/4 becomes 1/2 due to the initial spin states including a spin-0 ALP rather than a spin-1 photon. Therefore, for non-zero $g_{a\gamma\gamma}$, the production (via Primakoff) and the scattering (inverse) cross-sections involving both electron and nucleus in the atom have a $Z^2$ enhancement [36]. Finally, the ALP could interact with electrons through the inverse Compton-like process, $a + e^- \to \gamma + e^-$, which produces a photon from electron bremsstrahlung as well as an electron recoil for non-zero $g_{aee}$ with an enhancement factor of $Z$.

**Example experiments:** We describe below the neutrino experiments which will be utilized to investigate ALPs. For all these experiments, we plan to perform detailed analyses to estimate the sensitivity of the ALP parameter space using photons and electrons in the final states emerging from scattering and decays, reflecting the potential backgrounds from SM processes. Various beam energies at these experiments would allow us to investigate a wide range of ALP masses ($\sim$ 0 to multi GeV).

- DUNE near detectors [38]: A 120-GeV proton beam hits a graphite target, producing photons copiously via bremsstrahlung and decays of various mesons such as $\pi^0$, $\eta^0$ etc. GEANT4 simulation will be used to estimate the photon flux at the neutrino target, which would be converted into ALP flux using Primakoff conversion. The ALPs will be detected at the near detector complex (547 m away from the target) which contains liquid argon time projection chamber (LArTPC) near detector followed by a large-volume high-pressure gaseous argon TPC.

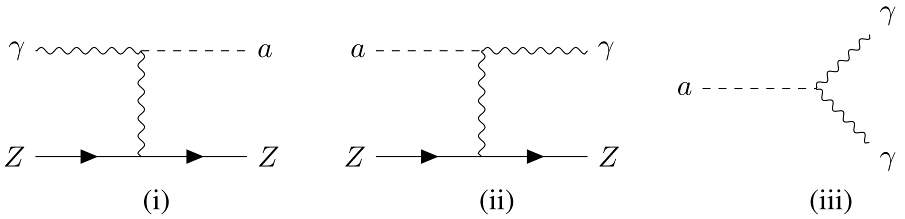

Figure 1: (i) Tree-level axion production through the Primakoff process. (ii) Tree-level axion detection through the inverse Primakoff process. In both cases the axion $a$ coherently scatters with the electric fields of the entire atomic system $Z \equiv (e^-, N)$. (iii) Axion decays in the detector.

The final set of detectors of the DUNE near detector, called SAND, contain a 3D scintillator tracker as an active neutrino target, a low density tracker and an electromagnetic calorimeter. Both the gaseous argon TPC and SAND are embedded in a solenoidal magnetic field of about 0.5 T. The TPCs will move off-axis for about 50% of the time while SAND will remain on axis.

- T2K ND280 [39]: The J-PARC proton beam (30 GeV energy) hits a graphite target and the ND280 detector is located at 280 m away from the target. It is composed of a few sub-detectors: Pi-Zero detector, two Fine-Grained scintillation detectors, and three TPCs. The ND280 detector will be upgraded adding extra TPCs for geometrical coverage, with a 3D scintillator tracker as an active neutrino target, and with timing detectors, and should start taking data in 2022. Also the proton source will be upgraded during that time. Note that the ND280 detector is also surrounded by a large magnet producing 0.2 T uniform horizontal field.
- Short-Baseline Near Detector (SBND) [40]: A 8 GeV proton beam hits the Be target. The 210 ton (112-ton active mass) LArTPC detector is located at a distance of 110 m from the target.
- ICARUS using the NuMI beam: ICARUS is a 476 ton effective mass LArTPC detector located on the Short-Baseline neutrino beam [41], like SBND, but at a distance of 600 m from the target. ICARUS acts also as a 6° off-axis detector for the intense 120 GeV proton NuMI beam, at a distance of 800 m from the corresponding proton-carbon target.

**Summary:** While the studies we present will focus on neutrino experiments in immediate and intermediate future, we are confident that ALP searches could continue through the experiments, beyond them, leveraging high intensity proton beams capable, large volume near detector facilities. So, this will be an important physics opportunity that can be taken in both the neutrino physics program and the rare process physics program throughout the coming decade and beyond.

# References

[1] R. D. Peccei and H. R. Quinn, *CP Conservation in the Presence of Instantons*, *Phys. Rev. Lett.* **38** (1977) 1440–1443.

[2] F. Wilczek, *Problem of Strong $P$ and $T$ Invariance in the Presence of Instantons*, *Phys. Rev. Lett.* **40** (1978) 279–282.

[3] S. Weinberg, *A New Light Boson?*, *Phys. Rev. Lett.* **40** (1978) 223–226.

[4] L. D. Duffy and K. van Bibber, *Axions as Dark Matter Particles*, *New J. Phys.* **11** (2009) 105008, [`0904.3346`].

[5] D. J. E. Marsh, *Axion Cosmology*, *Phys. Rept.* **643** (2016) 1–79, [`1510.07633`].

[6] M. Battaglieri et al., *US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report*, in *U.S. Cosmic Visions: New Ideas in Dark Matter College Park, MD, USA, March 23-25, 2017*, 2017. `1707.04591`.

[7] A. Ringwald, *Axions and axion-like particles*, 2014.

[8] K. Zioutas et al., *A Decommissioned LHC model magnet as an axion telescope*, *Nucl. Instrum. Meth.* **A425** (1999) 480–489, [`astro-ph/9801176`].

[9] CAST collaboration, V. Anastassopoulos et al., *New CAST Limit on the Axion-Photon Interaction*, *Nature Phys.* **13** (2017) 584–590, [`1705.02290`].

[10] IAXO collaboration, I. Irastorza et al., *The International Axion Observatory IAXO. Letter of Intent to the CERN SPS committee*, .

[11] Y. Kahn, B. R. Safdi and J. Thaler, *Broadband and Resonant Approaches to Axion Dark Matter Detection*, *Phys. Rev. Lett.* **117** (2016) 141801, [`1602.01086`].

[12] ABRACADABRA collaboration, C. P. Salemi, *First Results from ABRACADABRA-10cm: A Search for Low-Mass Axion Dark Matter*, in *54th Rencontres de Moriond on Electroweak Interactions and Unified Theories (Moriond EW 2019) La Thuile, Italy, March 16-23, 2019*, 2019. `1905.06882`.

[13] ADMX collaboration, S. J. Asztalos et al., *Large scale microwave cavity search for dark matter axions*, *Phys. Rev. D* **64** (2001) 092003.

[14] ADMX collaboration, N. Du et al., *A Search for Invisible Axion Dark Matter with the Axion Dark Matter Experiment*, *Phys. Rev. Lett.* **120** (2018) 151301, [`1804.05750`].

[15] D. F. Jackson Kimball et al., *Overview of the Cosmic Axion Spin Precession Experiment (CASPEr)*, `1711.08999`.

[16] B. M. Brubaker et al., *First results from a microwave cavity axion search at 24 $\mu$eV*, *Phys. Rev. Lett.* **118** (2017) 061302, [`1610.02580`].

[17] HAYSTAC collaboration, A. Droster and K. van Bibber, *HAYSTAC Status, Results, and Plans*, in *13th Conference on the Intersections of Particle and Nuclear Physics (CIPANP 2018) Palm Springs, California, USA, May 29-June 3, 2018*, 2019. `1901.01668`.

[18] ALPS collaboration, A. Spector, *ALPSII Status Report*, in *14th Patras Workshop on Axions, WIMPs and WISPs (AXION-WIMP 2018) (PATRAS 2018) Hamburg, Germany, June 18-22, 2018*, 2019. `1906.09011`.

[19] A. C. Melissinos, *Search for Cosmic Axions using an Optical Interferometer*, *Phys. Rev. Lett.* **102** (2009) 202001, [`0807.1092`].

[20] W. DeRocco and A. Hook, *Axion interferometry*, *Phys. Rev. D* **98** (2018) 035021, [`1802.07273`].

[21] H. Liu, B. D. Elwood, M. Evans and J. Thaler, *Searching for Axion Dark Matter with Birefringent Cavities*, *Phys. Rev. D* **100** (2019) 023548, [`1809.01656`].

[22] I. Obata, T. Fujita and Y. Michimura, *Optical Ring Cavity Search for Axion Dark Matter*, *Phys. Rev. Lett.* **121** (2018) 161301, [`1805.11753`].

[23] J. L. Feng, I. Galon, F. Kling and S. Trojanowski, *Axionlike particles at FASER: The LHC as a photon beam dump*, *Phys. Rev. D* **98** (2018) 055021, [`1806.02348`].

[24] A. Berlin, N. Blinov, G. Krnjaic, P. Schuster and N. Toro, *Dark Matter, Millicharges, Axion and Scalar Particles, Gauge Bosons, and Other New Physics with LDMX*, *Phys. Rev. D* **99** (2019) 075001, [`1807.01730`].

[25] LDMX collaboration, T. Åkesson et al., *Light Dark Matter eXperiment (LDMX)*, `1808.05219`.

[26] R. Volpe, *Search for exotic decays at NA62*, in *Meeting of the Division of Particles and Fields of the American Physical Society (DPF2019) Boston, Massachusetts, July 29-August 2, 2019*, 2019. `1910.10429`.

[27] A. Berlin, S. Gori, P. Schuster and N. Toro, *Dark Sectors at the Fermilab SeaQuest Experiment*, *Phys. Rev. D* **98** (2018) 035011, [`1804.00661`].

[28] S. Alekhin et al., *A facility to Search for Hidden Particles at the CERN SPS: the SHiP physics case*, *Rept. Prog. Phys.* **79** (2016) 124201, [`1504.04855`].

[29] W. M. Bonivento, D. Kim and K. Sinha, *PASSAT: Particle Accelerator helioScopes for Slim Axion-like-particle deTection*, *Eur. Phys. J. C* **80** (2020) 164, [`1909.03071`].

[30] J. B. Dent, B. Dutta, D. Kim, S. Liao, R. Mahapatra, K. Sinha et al., *New Directions for Axion Searches via Scattering at Reactor Neutrino Experiments*, *Phys. Rev. Lett.* **124** (2020) 211804, [`1912.05733`].

[31] XENON collaboration, E. Aprile et al., *Observation of Excess Electronic Recoil Events in XENON1T*, `2006.09721`.

[32] J. B. Dent, B. Dutta, J. L. Newstead and A. Thompson, *Inverse Primakoff Scattering as a Probe of Solar Axions at Liquid Xenon Direct Detection Experiments*, `2006.15118`.

[33] SUPERCDMS COLLABORATION collaboration, T. Aralis et al., *Constraints on dark photons and axionlike particles from the supercdms soudan experiment*, *Phys. Rev. D* **101** (Mar, 2020) 052008.

[34] C. Fu, X. Zhou, X. Chen, Y. Chen, X. Cui, D. Fang et al., *Limits on axion couplings from the first 80 days of data of the pandax-ii experiment*, *Physical Review Letters* **119** (Nov, 2017) .

[35] H. Primakoff, *Photoproduction of neutral mesons in nuclear electric fields and the mean life of the neutral meson*, *Phys. Rev.* **81** (1951) 899.

[36] Y.-S. Tsai, *AXION BREMSSTRAHLUNG BY AN ELECTRON BEAM*, *Phys. Rev. D* **34** (1986) 1326.

[37] D. Aloni, C. Fanelli, Y. Soreq and M. Williams, *Photoproduction of Axionlike Particles*, *Phys. Rev. Lett.* **123** (2019) 071801, [`1903.03586`].

[38] DUNE collaboration, B. Abi et al., *Long-baseline neutrino oscillation physics potential of the DUNE experiment*, `2006.16043`.

[39] J. R. Wilson, *The hyper-k near detector programme*, .

[40] R. A. et al., *A proposal for a three detector short-baseline neutrino oscillation program in the fermilab booster neutrino beam*, 2015.

[41] MICROBOONE, LAR1-ND, ICARUS-WA104 collaboration, M. Antonello et al., *A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam*, `1503.01520`.