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# Search for Axion-Like Particles at the Reactor Neutrino Facilities

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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
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**RF Topical Groups:** (check all that apply □/■)
□ (RF1) Weak decays of b and c quarks
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□ (RF5) Charged Lepton Flavor Violation (electrons, muons and taus)
■ (RF6) Dark Sector Studies at High Intensities
□ (RF7) Hadron Spectroscopy

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**Abstract:** This Letter of Interest discusses the opportunity of axion-like particle searches at reactor-based neutrino facilities which are featured by a very large flux of photons which can be converted into axion-like particles via the Primakoff effect with an atom and/or a Compton-like process with an electron in the reactor core. The produced axion-like particles then travel to a detector where they can leave signatures by decaying to a photon/electron pair and/or scattering off an atom/electron via the inverse Primakoff/Compton-like process.

**Introduction:** Models of axions are a well-motivated and extensively explored extension of the Standard Model (SM) due to the capability to address the strong CP problem [1–3] and to serve as a dark-matter candidate (e.g., Refs. [4–6]). This has inspired various theoretical and phenomenological studies (e.g., Ref. [7]) for investigating not only the original QCD axion but general axion-like particles (ALPs) in a wide range of models.

A variety of approaches have been adopted to explore parameter space of the ALP, especially in terms of its couplings to photons, electrons, and nucleons according to its mass. Examples 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], dark matter experiments: XENON [30, 31], SuperCDMS [32], PandaX [33] etc.

In this Letter of Interest, we discuss the exploration of ALP-photon and ALP-electron couplings at reactor neutrino experiments [34]. A reactor can produce not only neutrinos for the CE$\nu$NS measurement but photons with very high intensity, e.g., $\sim 10^{29}$ photons per year for a Giga-watt reactor. Our proposal in Ref. [31] is to make use of 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 ongoing and projected reactor neutrino experiments such as CONNIE, CONUS, MINER, $\nu$-cleus, and SoLid to detect ALPs produced from the photons at their and future reactors.

**ALP search strategy:** In order to explore the ALP parameter space, we focus on a generic model where the ALP can couple to either a photon or an electron with respective coupling strengths parameterized by $g_{a\gamma\gamma}$ and $g_{aee}$, as described by interaction terms in the Lagrangian of the form

$$\mathcal{L}_{\rm int} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu} - g_{aee} a \bar{\psi}_e \gamma_5 \psi_e \tag{1}$$

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 [see Figure 1(i)]. This interaction is governed by coupling $g_{a\gamma\gamma}$ and is enhanced by the coherency factor $Z^2$ where $Z$ is the atomic number. The differential cross-section for the forward scattering is [36, 37]

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

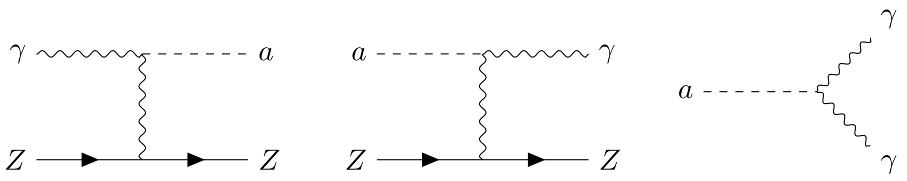
Here $\alpha = e^2/(4\pi)$ is the standard electromagnetic fine structure constant, $F^2(t)$ contains the atomic and nuclear form factors, and $|\vec{p}_a|$ is the magnitude of the outgoing three-momentum of the ALP at angle $\theta$ relative to the incident photon momentum. The square of the four-momentum 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 $m_a$. ALPs can also be produced through an $s$- plus $u$-channel Compton-like scattering process on electron targets $\gamma + e^- \to a + e^-$ [38–40].

Within the framework described here, once produced, the ALP can generate a detectable signal in several ways. First, the ALP could decay to two photons or an electron-positron pair [see Figure 1(iii)] with the well-known decay widths

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

which, in conjunction with the ALP energy, fix the decay length. Second, the ALP could be detected through the inverse Primakoff process $a + A \to \gamma + A$ [see Figure 1(ii)], which has the same differential cross-section as in Eq. (2), 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 and expected sensitivity reaches:** We performed a study to estimate the experimental sensitivity reaches expected under the proposed ALP search strategy, taking several benchmark reactor-based experiments




(i) (ii) (iii)

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

which are MINER, $\nu$-cleus, CONNIE, and CONUS [34]. Approximate specifications for their reactor and detector benchmarks are summarized in the below table. Background rates in DRU (kg$^{-1}$keV$^{-1}$day$^{-1}$) are based on the rates that appear in the region of interest (ROI) of each respective experiment. Exposures are based on a 3-year run period.

| Experiment | Core thermal power | Core proximity | Background rate in ROI | Exposure |
|---|---|---|---|---|
| MINER (Ge) | 1 MW | 2.25 m | 100 DRU | 4,000 kg·days |
| $\nu$-cleus ($CaWO_4$) | 4 GW | 40 m | 100 DRU | 10 kg·days |
| CONNIE (Si CCD) | 4 GW | 30 m | 700 DRU | 100 kg·days |
| CONUS (Ge PPC) | 4 GW | 17 m | 100 DRU | 4,000 kg·days |

Our analysis using photons and electrons in the final state emerging from scattering and decays suggests that these experiments can reach $g_{a\gamma\gamma} \sim 10^{-6}$ GeV$^{-1}$ for ALP of a few MeV and $g_{aee} \sim 10^{-5}$–$10^{-6}$ for $m_a \lesssim 1$ MeV, allowing us to explore a wide range of parameter space that the existing laboratory-based ALP searches have never probed [34]. In particular, for the parameter space of $g_{a\gamma\gamma}$, these experiments can be sensitive to (part of) the "cosmological triangle" region. Overall, they can provide complementary information.

**Future plans:** It may be interesting to explore the data collected by near reactor experiments like MINER, designed for very short distance neutrino oscillations searches. As an example, SoLid [41] is a new generation neutrino experiment that aims to address key challenges for high precision reactor neutrino measurements at very short distances. The 1.6 ton plastic scintillator detector, consisting of 5x5x5 cm$^3$ sized cubes, is placed between 6 and 9 meters from the core of a research reactor with a power of 60-80 MW. The detector has an energy resolution of about $14\%\sqrt{E(\mathrm{MeV})}$ for $E > 0.5$ MeV. About 400 days with reactor-on data have been collected so far and the experiment will continue to take data with an upgraded detector in the next years. Specific experimental triggers may be required to maximize the sensitivity for axion decay or scattering signatures, and can be studied within this project.

**Summary:** While the studies we present focus on reactor neutrino experiments in the present and near future, we believe that ALP searches could continue through the experiments, beyond them, leveraging high-intensity low-energy neutrino experiments including CE$\nu$NS. So, this will be an important physics opportunity that can be taken in the neutrino physics program throughout the coming decade.

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