New Directions for Axion Searches via Scattering at Reactor Neutrino Experiments

James B. Dent, Bhaskar Dutta, Doojin Kim, Shu Liao, Rupak Mahapatra, Kuver Sinha, and Adrian Thompson

1Department of Physics, Sam Houston State University, Huntsville, TX 77341, USA
2Mitchell Institute for Fundamental Physics and Astronomy, Department of Physics and Astronomy, Texas A&M University, College Station, TX 77845, USA
3Department of Physics and Astronomy, University of Oklahoma, Norman, OK 73019, USA

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Introduction. - Axions are a well-motivated and extensively explored extension of the Standard Model (SM) both for their ability to address the strong CP problem [1–3], and for serving as a dark matter candidate (see, for example, the reviews [4–6]). Theoretical studies have branched away from solely investigating the original QCD axion (the pseudoscalar which can solve the strong CP problem) and have incorporated general axion-like particles (ALPs) into a range of models.

Axions and ALPs are undergoing a period of intense experimental scrutiny from a wide array of approaches including helioscopes and haloscopes that exploit an axion-photon coupling such as Abracadabra [7, 8], ADMX [9, 10], CASPER [11], CAST [12, 13], HAYSTAC [14, 15], IAXO [16], light shining through walls experiments including ALPSII [17], and additional experiments that exploit the possible axion-photon coupling through interferometry [18, 19] such as ADBC [20] and DANCE [21]. Additionally there are a variety of current and proposed beam dump and fixed target experiments that can search for $a \rightarrow \gamma \gamma$ decays or axion bremsstrahlung from electrons including FASER [22], LDMX [23, 24], NA62 [25], SeaQuest [26], and SHiP [27]. For a recent review of the current status and future prospects of axion searches at collider see, for example, Ref. [28]. Neutrino experiments such as NOMAD [29] have been used as ALP searches, and there are proposals such as PASSAT [30] which are hybrids of the beam dump and helioscope approaches. Dark matter direct detection experiments including XMASS [31], EDELWEISS-III [32], LUX [33], PandaX-II [34], Xenon1T [35], and SuperCDMS [36], which have excellent electron recoil measurement capabilities, have also been used to search for ALP-electron scattering.

An ALP field $a$ could couple to SM particles through a myriad of operators, but those of interest in this work will be those of dimension-five coupling $g_{a\gamma\gamma}aF_{\mu\nu}F^{\mu\nu}$ as well as to electrons through the dimension-four coupling $g_{ace}a\bar{\psi}\gamma^5\psi$.

In this paper, we will focus on a new direction in ALP searches involving low-energy detectors at a nuclear reactor facility that will exploit both the copious photon production (and therefore, possible ALP production) and low-energy capabilities of the current detector technology. Specifically, we discuss the capabilities of probing ALPs for the upcoming search for coherent elastic neutrino-nucleus scattering (CEνNS) by the Mitchell Institute Neutrino Experiment at Reactor (MINER) Collaboration [37], while the proposed search strategy is generic. This experiment consists of an array of low-threshold cryogenic germanium detectors sited a few meters from the core of the 1MW nuclear reactor at the Nuclear Science Center (NSC) at Texas A&M University. The nuclear reactor core will produce a copious amount of photons, which can then produce ALPs via photon scattering off of the material within the reactor tank. On the detection side, the ALPs can directly scatter off of detector nuclei or electrons, as well as decay in flight to photon or electron-positron pairs, providing a constraint on either the ALP-photon or ALP-electron coupling, respectively.

In a previous reactor based investigation by the TEXONO Collaboration [38], ALP production was modeled as arising from neutron capture or nuclear de-excitation with a branching ratio to ALPs (relative to photon production) that depends on the ALP mass, $m_a$, through an ALP-nucleon coupling, thus leading to weakening constraints as $m_a$ decreases. In the present work, however, we adopt a minimal approach where no ALP-nucleon coupling is assumed, and ALPs are produced
via photon-induced scattering processes. These produce $m_a$-independent bounds for $m_a \lesssim 0.1$ MeV, allowing for broader coverage of the parameter space. Future work will consider inclusion of the nucleon coupling, which can improve sensitivity in some regions of parameter space.

We demonstrate that the current germanium configuration for MINER can quickly become the most sensitive laboratory-based detector for $g_{a\gamma\gamma}$ within an ALP mass range of $\sim (1 - 10^6)$ eV, and gain access to a wide swath of new parameter space in a similar mass range over several orders of magnitude in the coupling $g_{a\gamma\gamma}$. These results speak to the tremendous opportunity for exploration of the ALP mass and coupling space by low threshold detectors at nuclear reactor facilities and/or CEνNS experiments.

**ALP Production and Detection.** In this work we will focus on a generic model where the ALP, a pseudoscalar $a$, 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 $F_{\mu \nu}$ 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 $\gamma(p_1) + N(p_2) \rightarrow a(k_1) + N(k_2)$ [39], where $N$ is a nuclear target (Fig. 1). This interaction proceeds through a $t$-channel photon exchange. The momentum rate is governed by the strength of the coupling $g_{a\gamma\gamma}$. This process is enhanced by the coherency factor $Z^2$ for momentum transfers $q \lesssim 1/R_N$ where $R_N$ is the target radius and $Z$ is the atomic number. The forward scattering differential cross-section is [40, 41]

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

We will use superscripts $p$ and $d$ to distinguish between production and detection cross-sections, respectively. Here $\alpha = e^2 / (4\pi)$ is the standard electromagnetic fine structure constant, $F^2(t)$ is a form factor which encodes the momentum dependence of the nuclear interaction, and $|\vec{p}_a|$ is the magnitude of the outgoing three-momentum of the ALP at the angle $\theta$ relative to the incident photon momentum. The square of the four-momentum transfer is given by $t = (p_1 - k_1)^2 = m_a^2 + E_\gamma (E_a - |\vec{p}_a| \cos \theta)$ 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 $\gamma + e^− \rightarrow a + e^−$ which has a differential cross section [42, 43]

$$\frac{d\sigma_{C}^{d}}{d\Omega} = \frac{Z_{\gamma}^2 g_{a\gamma\gamma}^2 a E_\gamma}{8\pi m_a^2 \vec{p}_a} \left( \frac{1}{(2m_e E_a + m_a^2)^2} - \frac{4m_e E_\gamma}{(2m_e E_a + m_a^2)^3} \right)$$

where $m_e$ is the electron mass, $s$ is the usual Mandelstam variable $(s - m_a^2 = 2E_\gamma m_e$ in the electron rest frame), and $x$ is the fractional light cone momentum, which can take values between 0 and 1 in the light cone frame. In the laboratory frame, one may perform a change of variables using $x = 1 - \frac{E_a}{E_\gamma} + \frac{m_a^2}{2E_\gamma m_e}$.

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

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

which, in conjunction with the ALP kinetic energy, fix the decay length. Secondly, the ALP could interact with a nucleus through the inverse Primakoff process $a + N \rightarrow \gamma + N$, 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. Finally, the ALP could interact with electrons through a Compton-like process similar to their production from electrons, $a + e^- \rightarrow \gamma + e^-$, which produces photons from electron bremsstrahlung as well as electron recoils. This process has a differential cross-section of the form [44, 45]

$$\frac{d\sigma_{C}^{d}}{d\Omega} = \frac{Z_{\gamma}^2 g_{a\gamma\gamma}^2 a E_\gamma}{8\pi m_a^2 \vec{p}_a} \left( \frac{1}{(2m_e E_a + m_a^2)^2} - \frac{4m_e E_\gamma}{(2m_e E_a + m_a^2)^3} \right)$$

**The MINER Experimental Setup.** - The MINER experiment consists of SuperCDMS-style cryogenic germanium detectors situated at 4.5 m from the core of a TRIGA type 1 MW reactor with low enriched $^{235}$U at the NSC (the reactor-detector system allows for closer proximity down to $\sim 2$ m for the next phase). Though the experiment was established for detection of CEνNS, it is also ideally situated for ALP searches in previously unexplored regions of ALP mass-coupling parameter space. This is due to the combination of a substantial photon flux of $10^{19} \gamma / s$ from the reactor, the nearness of the detectors, their low-threshold sensitivity, and detection
through both scattering and decay channels. As an example of the reach for this experimental layout, for ALPs of mass $m_a = 1 \text{ MeV}$ and photon coupling $g_{a\gamma\gamma} = 10^{-6} \text{ MeV}^{-1}$, the photon flux from ALP decay will be approximately $13.6 \text{ cm}^{-2}\text{s}^{-1}$, with an ALP flux of $72.0 \text{ cm}^{-2}\text{s}^{-1}$. Depending on the choice of coupling and ALP mass, the photon rates may vary in comparison between ALP scattering and decay.

Estimation of the ALP detection rate is performed as follows. We take a reactor photon spectral flux which we restrict to $> 25 \text{ keV}$ in energy due to the binning of the background simulation [37], taken at the reactor core. We then convolve this flux with the Primakoff or Compton cross-sections to produce ALPs from photons scattering with the core material, in this case approximated by a core of pure Thorium ($Z = 90$, averaging across atomic numbers in the core). ALPs are then allowed to propagate through the shielding material until they either decay in flight or scatter off the detector material.

The convolution performed here is similar to the one in the TEXONO analysis, except in this case the production mechanism via Primakoff or Compton conversion imposes a branching ratio $\Gamma_a/\Gamma \equiv \sigma_a^{\text{SM}}/\sigma_a^p + \sigma_a^{\text{SM}}$. Here $\sigma_a^{\text{SM}} = \sigma_a^C, \sigma_a^p$ is the Compton or Primakoff axion-production cross-section, respectively, and $\sigma_a^{\text{SM}}$ represents the total photon scattering cross-section against core material taken from the Photon Cross Sections Database [46]. The event yield $S$ from ALP scattering is therefore given by, in the Primakoff case,

$$S = \frac{N_T \sigma_a^{\text{SM}}}{4\pi \ell_d^2} \int \frac{d\Phi_\gamma}{dE_\gamma} \cdot \frac{\Gamma_a}{\Gamma} \cdot P_{\text{surv}} \ dE_\gamma$$ (7)

where $N_T$ is the number of target atoms, $\sigma_a^{\text{SM}}$ is the Primakoff scattering cross-section, $\frac{d\Phi_\gamma}{dE_\gamma}$ is the differential reactor photon flux and survival probability $P_{\text{surv}} = \exp\left(-\frac{\ell_s}{\tau_a}\right)$ for a core-detector proximity $\ell_d$, axion lifetime $\tau$, and momentum $p_a$. In the Compton case, unlike the Primakoff case whose axions directly inherit their energies from forward-scattered photons, we must also include the differential probability of producing an axion with energy $E_a$, giving an additional factor $\frac{1}{\sigma_a} \frac{d\sigma_a}{dE_a}$ and an additional integration over axion energies.

To keep the analysis simple, no ALP flux attenuation is applied from scattering inside the shielding; however, we also assume no ALP production inside the shielding, nor do we include other channels of ALP production (e.g. axion bremsstrahlung) inside the core, leaving the signal yield estimate on the conservative side.

Lastly, diphoton and electron-positron pair production from ALP decay may also contribute to the event yield, but the ALP must bypass the shielding sections in order for the decay products to be seen by the detector; hence, we take the probability of decay inside the detector volume:

$$P_{\text{decay}} = 1 - e^{-\frac{\ell_s}{\tau_a}} \left(1 - e^{-\frac{\Delta\ell_s}{\tau_a}}\right)$$ (8)

for a shielding length $\ell_s$ and detector length $\Delta \ell$.

The detected photon spectrum from Primakoff-produced ALPs converting to photons or decaying to diphoton pairs in the detector is shown in Fig. 2 in DRU units (counts/day/kg/kev). As from Eq. (2), the scattering spectrum pictured is independent of $m_a$ in the forward limit, while the ALP decay-driven photon rate is dependent on both $m_a$ and $g_{a\gamma\gamma}$ via Eq. (4). The backgrounds pictured stem from sources of radiochemical emission and are expected to remain flat and attenuate quickly by $2.6 \text{ MeV}$ thalium endpoint, although the exact spectrum shape is not empirically known yet.

**Results.** - Having set the stage for the ALP search...
for the MINER experiment, we are now in a position to present its reach on both ALP-photon and ALP-electron couplings over a range of ALP masses. We evaluate limits on the ALP signal sensitivity for Ge as well as CsI detectors at a select set of benchmark scenarios, keeping only one coupling turned on at a time.

We take a future detector proximity to the reactor core of 2.5 m for both Ge and CsI. A Ge detector of 4 kg is already in production, and for the CsI detector we consider the scheduled mass of 200 kg and a 2-ton future mass point. As a conservative evaluation, we calculate the projected limits on the ALP mass and couplings via a single energy bin analysis using $\kappa = \frac{N_s}{\sqrt{N_s + N_b}}$ as a test statistic where $N_s$ and $N_b$ are the integrated signal and background events, respectively. Background rates for Ge are estimated from preliminary studies as 0.006 DRU, while for CsI we take a reference background rate of 0.0033 DRU as reported by the KIMS Collaboration for their CsI setup [47]. For Compton-like ALP detection, since the final state of $\gamma + e^-$ is more readily identifiable and has reducible backgrounds, we assume a signal-only model in that case.

Finally, it is well known that a large swath of the parameter space for ALPs and ALP-like particles is constrained by a variety of astrophysical processes [48], in addition to laboratory searches. There are a variety of issues involving both model varieties and uncertainties in the astrophysical environments [49] which lead us in this work to focus solely on laboratory searches which control both the production and detection sectors of the ALP processes.

Fig. 3 (top) shows the resulting $\kappa = 2$ contours (≈ 95% C.L.) on $(m_a, g_{aee})$ for Ge and CsI for ALPs coupled purely to photons. The flat limit for $m_a \leq 10^4$ eV is set by ALP scattering in the detector material and is $m_a$-independent (the reactor photon flux producing the axion is also constant in this energy range, originating from the single energy bin below 25 keV), while the limit peaked at $m_a \sim 4$ MeV is set by the $a \rightarrow \gamma \gamma$ rate which depends on the distance from the flux source and the ALP decay length.

Fig. 3 (bottom) shows similar limits on $(m_a, g_{aee})$ for Ge and CsI for ALPs coupled purely to electrons. The limits are dominated by ALP’s scattering off the detector material. Contributions from ALP decay $a \rightarrow e^+e^-$ re-
quire $m_a > 2m_e \approx 1 \text{ MeV}$ and a large enough coupling in order to have a decay length shorter than the detector-reactor proximity, we are not relevant in the parameter space shown. We see the sensitivity quickly diminishes as $m_a$ approaches 1 MeV since the ALP production rate is kinematically limited by $s \geq (m_a + m_e)^2$ and this enforces a low energy cutoff in the reactor photon spectrum which is already quickly falling. In the low $m_a$ limit, sensitivity flattens out as the ALP-electron scattering differential cross-section [Eq. (6)] becomes $m_a$-independent (again, the reactor photon flux is constant arising from the single energy bin below 25 keV).

**Summary.** - This work has demonstrated the exciting and new possibility of highly sensitive ALP searches from ALP scattering processes with currently existing low-threshold detectors at nuclear reactor facilities, with a specific focus on the MINER experiment. The advantages of such configurations are manifest in the large photon (and subsequently ALP) production from a reactor, proximity of the detectors to the core, and the capability of detecting either ALP decay to photons or electron scattering within the detector. The MINER experiment can improve the current leading bounds by $\sim 10-50\%$ for the ALP mass range of $m_a \approx 10^2 - 10^6$ eV for ALP-photon couplings. For ALP-electron couplings, MINER can make dramatic strides in wholly uncharted mass-coupling territory for $m_a \approx 1 - 10^5$ eV over several orders of magnitude in the coupling. Though this letter has been focused on the existing MINER experiment with a 4-kg payload of germanium detectors, the possibility exists to further enhance the depth of coverage for the planned installations at MINER with new target materials (of $\sim 100$ kg mass) such as CsI and LXe, as well as the possibility that GW-level power reactors could also implement similar detection schema with their relatively enhanced photon production. In addition to reactor based searches, stopped pion experiments also have a high photon flux which can be leveraged for similar ALP searches [50].

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