

MINER reactor based search for axionlike particles using sapphire (Al_2O_3) detectors

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The absence of definitive results for WIMP dark matter has sparked growing interest in alternative dark matter candidates, such as axions and axionlike particles (ALPs), which also provide insight into the strong CP problem. The Mitchell Institute Neutrino Experiment at Reactor (MINER), conducted at the Nuclear Science Center of Texas A&M University, investigated ALPs near a 1 MW h TRIGA nuclear reactor core, positioned approximately 4 m away. This experiment employed cryogenic sapphire detectors with a low detection threshold (≈ 100 eV), equipped with a transition edge sensor capable of detecting athermal phonons. Due to the low-background environment, we were able to exclude ALPs with axion-photon coupling and axion-electron coupling as small as $g_{a\gamma\gamma} = 10^{-5}$ and $g_{aee} = 10^{-7}$, respectively. Energy depositions below 3 keV were not considered and remain blinded for our coherent elastic neutrino-nucleus scattering analysis. This is the first result demonstrating the MINER experiment's potential to probe low-mass ALPs, enabled by its low-threshold detector and proximity to a reactor.

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I. INTRODUCTION

One of the most compelling solutions to the strong CP problem involves introducing a new broken symmetry, known as the Peccei-Quinn (PQ) symmetry, which naturally and dynamically cancels the CP violation in the strong interaction [1–3]. A direct consequence of this symmetry is the emergence of a hypothetical pseudoscalar particle

called the axion [4,5]. Axions and their generalizations, axionlike particles (ALPs), have attracted significant experimental interest due to their potential role in particle physics and cosmology.

Experimental searches for axions and ALPs leverage their coupling to photons in a variety of setups. Helioscope experiments such as CAST [6,7] and the future IAXO [8] seek axions emitted by the Sun, while haloscope experiments such as ADMX [9,10], Abracadabra [11,12], and HAYSTAC [13,14] aim to detect axions within a strong magnetic field. Light-shining-through-wall experiments such as ALPS II [15] attempt to produce and regenerate axions under controlled laboratory conditions. Furthermore, solar axions produced through nuclear

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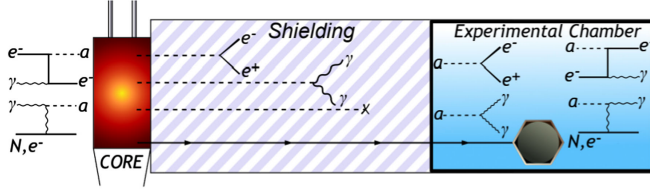


FIG. 1. A schematic illustration of axionlike particles (ALPs) and their interactions in a reactor neutrino experiment. On the left, the production of ALPs is shown, while the right highlights their scattering and decay possibilities. ALPs may decay inside the reactor shielding, evading detection (dashed lines). Alternatively, ALPs that free-stream through the shielding (solid lines) can be detected via the inverse Primakoff process, inverse Compton scattering channels, or decay channels.

transitions can be constrained by resonant absorption in laboratory nuclei [16–21].

Reactor-based experiments provide a unique opportunity for axion searches, since they offer a controlled environment for both axion production and detection. The MINER experiment at Texas A&M University employs an array of low-threshold cryogenic sapphire detectors placed 4 meters from a 1 MWh TRIGA reactor core [22]. This setup enables the search for ALPs produced via photon interactions within the reactor tank. ALPs can be detected through their scattering off nuclei and electrons in the detector, or via their decay into photons or electron-positron pairs, allowing constraints on both axion-photon and axion-electron couplings. A schematic of the experimental setup is shown in Fig. 1. Similar reactor-based experiments such as CONUS [23], CONNIE [24], and ν -cleus [25] employ different detector technologies to probe ALPs. Although astrophysical observations also provide constraints on the ALP parameter space, laboratory experiments offer a direct and controlled alternative, avoiding uncertainties associated with astrophysical modeling.

This paper is structured as follows: Sec. II presents the theoretical framework, including the ALP production mechanisms in the reactor, the detection methods, and the experimental sensitivity. Section III describes the experimental setup, detailing the reactor, detector configuration, data acquisition process, and shielding techniques. In Sec. IV, we present the experimental results, followed by an exclusion limit on ALP searches in the relevant parameter space. Finally, in Sec. V, we discuss our conclusions and future improvements to enhance the sensitivity of the experiment and to extend its reach to unexplored regions of the ALP parameter space.

II. ALP PRODUCTION AND DETECTION

The interaction Lagrangian for the axion-like particle (ALP) is given by

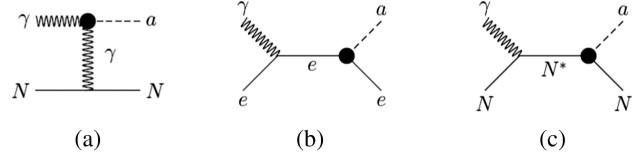


FIG. 2. Mechanisms for producing ALPs at the reactor facility. (a) the Primakoff process ($\gamma + N \rightarrow a + N$, where N is the atomic target). (b) the Compton-like process ($\gamma + e^- \rightarrow a + e^-$). (c) nuclear deexcitation ($\gamma + N \leftrightarrow N^* \rightarrow a + N$) [28,29]. Black points are vertices where the axionlike particle is coupled to another particle.

$$\mathcal{L}_{\text{int}} \supset -\frac{1}{4}g_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu} - g_{aee}a\bar{\psi}_e\gamma_5\psi_e - a\bar{\psi}_n\gamma_5(g_{ann}^{(0)} + \tau_3 g_{ann}^{(1)})\psi_n, \quad (1)$$

where $F^{\mu\nu}$ represents the electromagnetic field strength tensor, and its dual is defined as $\tilde{F}^{\mu\nu} = \epsilon^{\mu\nu\rho\sigma}F_{\rho\sigma}$. The field a denotes the axion, while ψ_e and ψ_n represent the electron Dirac spinor and the proton-neutron isospin doublet, respectively. The parameters $g_{a\gamma\gamma}$ and g_{aee} denote the axion-photon and axion-electron couplings, respectively, both expressed in units of GeV^{-1} [26]. The quantities $g_{ann}^{(0)}$ and $g_{ann}^{(1)}$ refer to the isosinglet and isotriplet axion-nucleon couplings, respectively, and τ_3 is the third Pauli matrix.

A reactor generates high-energy photons through fission processes [27]. These photons can interact with reactor materials, specifically ^{235}U in our case, leading to the production of ALPs through the Primakoff process, a Compton-like process, and nuclear deexcitation. Figure 2 illustrates these three photon-induced mechanisms responsible for ALP production within the reactor.

We will focus on a model where the ALP can be produced through photon or electron coupling and calculate the sensitivities for ALP-photon and ALP-electron couplings. For more information regarding nuclear deexcitation, refer to Refs. [28,30].

Once ALPs are produced, they can be detected through photon production at the detection site via the inverse Primakoff process, $a + N \rightarrow \gamma + N$, where N represents the atomic target. Additionally, ALPs can interact with electrons through an inverse Compton-like process, $a + e^- \rightarrow \gamma + e^-$, resulting in photon production. ALPs may also decay into two photons or an e^-/e^+ pair within the detector material, depending on their lifetime. These detection channels are illustrated in Fig. 1.

In this work, we predominantly adopt the minimal ALP assumption, which allows for ALP-SM couplings governing both the production and detection processes of ALPs [31]. As shown in Fig. 2(a), the Primakoff process occurs through a t -channel virtual photon exchange, with the production rate depending on the coupling strength

$g_{a\gamma\gamma}$ [31]. The differential cross section for the production of ALPs via the Primakoff process in the reactor core is given by [32,33]

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

where $t = (p_1 - k_1)^2 = m_a^2 + E_\gamma(E_a - |\overline{p}_a| \cos\theta)$ is the square of the four-momentum transfer, $\alpha = \frac{e^2}{4\pi}$ is the standard electromagnetic fine structure constant, Z is the atomic number of the target nucleus, $F(t)$ is the form factor, $|\overline{p}_a|$ is the magnitude of the ALP's outgoing three-momentum at the angle θ relative to the incident photon momentum, E_γ is the incident photon energy, and E_a is the energy of the ALP. It is important to note that the production cross section is enhanced by a coherency factor Z^2 , which increases the sensitivity of our experiment to ALP production and detection through the Primakoff channel compared to other processes. The differential cross section for the inverse Primakoff process follows the same form as in Eq. (2), with the front factor changing from $\frac{1}{4}$ to $\frac{1}{2}$, since the initial spin states involve a spin-0 ALP instead of a spin-1 photon. The ALP event yield via the inverse Primakoff process is estimated by the convolution of the detection rate with the reactor photon flux as follows [31]:

$$S(\text{scattering}) = \Delta t \frac{N_T}{4\pi l_d^2} \int dE_\gamma \sigma_p^d \frac{dN_\gamma}{dE_\gamma} \frac{\sigma_p^p}{\sigma_p^p + \sigma_{\text{SM}}} P_{\text{surv}}^\gamma, \quad (3)$$

where Δt is the data-taking time, N_T is the number of target atoms, σ_p^d is the Primakoff scattering cross section in the detector, $\frac{dN_\gamma}{dE_\gamma}$ represents the differential photon flux at the detector ($\text{time}^{-1} \text{Energy}^{-1}$), σ_p^p is the total Primakoff axion production cross section, σ_{SM} represents the total photon scattering cross section against core material taken from the Photon Cross Sections Database [34], and P_{surv}^γ denotes the ALP survival probability, accounting for the likelihood that ALPs travel from the reactor core to the detector without decaying:

$$P_{\text{surv}}^\gamma = \exp\left(-\frac{l_d}{v_a \tau_a^\gamma}\right), \quad (4)$$

where v_a is the axion velocity, l_d is the core-detector distance, and $\tau_a^\gamma = \frac{E_a}{m_a} \frac{1}{\Gamma(a \rightarrow \gamma\gamma)}$ is the axion decay lifetime.

Similarly, for the decay of an ALP into two photons, the signal is estimated as follows [31]:

$$S(\text{decay}) = \Delta t \frac{N_T}{4\pi l_d^2} \int dE_\gamma \sigma_p^d \frac{dN_\gamma}{dE_\gamma} \frac{\sigma_p^p}{\sigma_p^p + \sigma_{\text{SM}}} P_{\text{surv}}^\gamma P_{\text{decay}}^\gamma, \quad (5)$$

where P_{decay}^γ is the axion decay probability inside the detector volume,

$$P_{\text{decay}}^\gamma = \exp\left(-\frac{l_d}{v_a \tau_a^\gamma}\right) \left[1 - \exp\left(-\frac{\Delta l}{v_a \tau_a^\gamma}\right)\right], \quad (6)$$

and Δl is the fiducial detector length. Note that the axion decay width in its rest frame, given by $\Gamma(a \rightarrow \gamma\gamma) = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}$, scales as m_a^3 . Consequently, heavier ALPs are more likely to decay, even for smaller values of the coupling constant, so $g_{a\gamma\gamma}$ typically decreases with increasing m_a . As the decay lifetime is inversely proportional to the decay width, this leads to a rapid decrease in sensitivity to light axions whose decay length exceeds the experimental flight path. Consequently, heavier axions are more constrained by decay limits [35]. Considering Eqs. (2) and (3), we obtain a relation for the ALP signal rate through scattering (decay processes). An analogous analysis is performed for the axion-electron coupling, where the contribution from atomic ionization via axion absorption is disregarded in the present work to provide preliminary results. However, this contribution will be incorporated in future studies to refine the sensitivity estimates [36]. Following the approach in Ref. [31], we can calculate axion production via Compton scattering and estimate the corresponding signal rate through inverse Compton scattering. In the following section, we will discuss the data acquisition process and the background count rate, which set a lower limit on the ALP signal rate. This allows us to determine the sensitivity to the couplings $g_{a\gamma\gamma}$ and g_{aee} as a function of m_a .

III. EXPERIMENTAL SETUP

This experiment is conducted at the Nuclear Science Center (NSC) at Texas A&M University. This section describes the specific details regarding the reactor, detector, and shielding methods to limit the backgrounds. We will also describe the data acquisition process and event reconstruction at the end.

A. Reactor (gamma source)

The reactor at the Nuclear Science Center (NSC) is of the TRIGA type (testing, research, isotopes, general atomics) and can operate at powers up to 1 MW_{th} using low-enriched ^{235}U as fuel. This reactor is equipped with a movable core, allowing detectors to be positioned in close proximity to the core, down to a distance of 2 m. The present experiment was conducted with the reactor operating at an actual power of approximately 800 kW and a core-to-detector distance of about 4 m. During operation, the core produces a substantial photon flux of $\approx 10^{10} \text{ cm}^{-2} \text{ s}^{-1}$, with an end-point energy around 10 MeV. Figure 3 shows the photon flux spectrum originating from the reactor core [37]. The gamma-ray spectrum is dominated by neutron interactions,

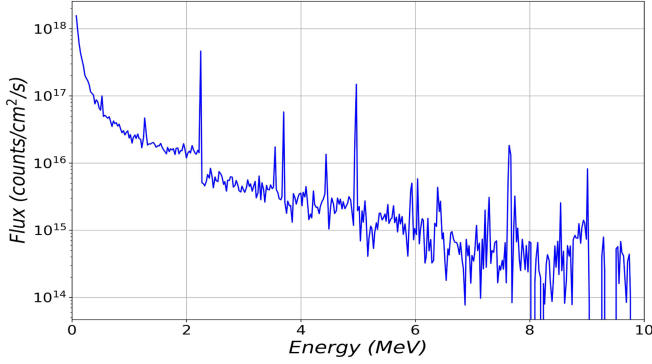


FIG. 3. Simulated photon flux at a distance of 4 m from the reactor core, obtained using the Monte Carlo N-Particle (MCNP) core model. Some of the strongest capture gamma lines in thorium-based reactors are evident at 2.6 MeV (one of the strongest transitions in ^{233}Th), 4.0 MeV (the deexcitation of higher-energy nuclear states), and 4.8–5.0 MeV (a common gamma line from neutron interactions in thorium [38]).

leading to emission lines similar to those observed in other ^{235}U -based reactors.

B. Detector payload

This experiment employs three cylindrical sapphire detectors, each with a diameter of 3 inches, stacked vertically in a tower configuration within a copper shield. Two of the detectors have a thickness of 1 cm, while the middle one has a thickness of 4 mm with a total mass of 435 g. A schematic representation of this tower setup is shown in Fig. 4. Sapphire (Al_2O_3), in its single-crystal form, has a density of approximately 3.98 g/cm^3 and is classified as a low-yield scintillator.

Each detector is constructed with four readout channels, with three inner channels and one outer circular channel, as illustrated in Fig. 5. Each channel is instrumented with an array of tungsten transition edge sensors (TESs) [39],

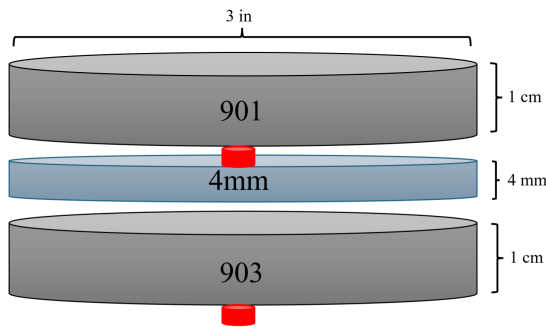


FIG. 4. A schematic representation of the three detectors, with the outer detectors labeled “901,” “903” (with thickness 1 cm and mass 181 g), and “4 mm” (with thickness 4 mm and mass 72 g), stacked in a tower configuration with a gap of 2 mm between each of them. For calibration purposes, two ^{55}Fe sources are placed between the 901 and 4 mm detectors, and below the 903 detector.

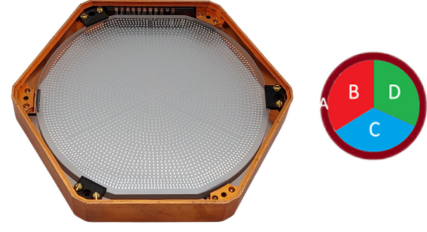


FIG. 5. A 4 mm sapphire detector in a copper housing. Reflection of the fabricated phonon sensors can be seen due to the transparency of the sapphire crystal. It is equipped with three inner channels, which provide fiducialization for event reconstruction in the bulk of the crystal, and an outer channel.

which are photolithographically fabricated in parallel on one side of the crystal to measure athermal phonons generated from lattice interactions. The TESs are voltage-biased and operate within the superconducting-to-normal transition region. To enable readout through the TES sensors, the detector assembly was installed in a cryogenic system—a BLUEFORS dilution refrigerator—maintained at an operational base temperature of 8 mK [40]. This ultra-low-temperature environment is crucial for ensuring the TES sensors operate within their superconducting transition region, thereby achieving the necessary sensitivity to detect athermal phonon signals generated by particle interactions in the detectors.

Although the experiment was originally designed for the detection of coherent elastic neutrino-nucleus scattering (CE ν NS), it is also well suited for ALP searches in the low-mass region of the (g_{eff}, m_a) parameter space. This is enabled by the combination of a substantial photon flux of $10^{10} \text{ cm}^{-2} \text{ s}^{-1}$ from the reactor, the close proximity of the detectors to the core, the detectors’ low-threshold sensitivity, and the capability to detect ALPs through both scattering and decay channels.

C. Shielding

In this experiment, the detector tower is enclosed within hermetic shielding to suppress the gamma-ray background. To mitigate potential neutron backgrounds, the copper housing is additionally shielded by four layers of lead, a 2 mm-thick borated rubber layer, and an 8-inch layer of water bricks. Additionally, as a veto and shielding against thermal neutrons, Bicron-412 plastic scintillators with a thickness of 2 inches were placed around the experimental setup. A schematic of the shielding is shown in Fig. 6.

D. Data acquisition

For data acquisition, we have used a VME-based CAEN V1740D digitizer which is a 30 MHz analog-to-digital converter with 64 channels, 12-bit resolution, and a 62.5 MS/s sampling rate with DPP-QDC (Digital Pulse Processing—Charge to Digital Converter) firmware, which

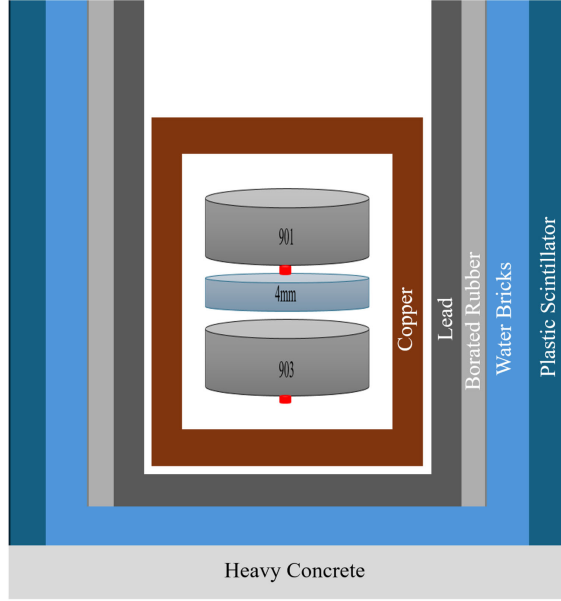


FIG. 6. MINER experiment shielding.

can process the input pulses to produce integral (energy) and trigger time stamps for each event in the detector.

The data acquisition process consists of two distinct phases: reactor-off and reactor-on. The reactor-off phase is used to measure background data, providing a baseline for setting a lower limit on the possible ALP signal region and modeling the background spectrum. In the reactor-on mode, we use its spectrum in setting the exclusion limit to the present work. Given that our setup comprises three detectors stacked in a tower configuration, every detected event must be carefully analyzed to determine its origin. In the following section, we will detail the criteria for defining signal events and the methods used to reject noise.

IV. ANALYSIS AND RESULTS

This section describes the definition of single-scatter events and detector calibration and compares the resulting spectra with estimated ALP signals to set exclusion curves.

A. Single-scatter event definition

Due to the rarity of ALP-induced events, only events detected by a single detector are considered as possible ALP events, which are called here single-scatter events. The focus on these events is motivated by the expectation that multiple-scatter events (i.e., those involving more than one detector) are predominantly associated with background sources such as neutrons, which are capable of interacting with multiple detectors. In contrast, ALP-induced events are expected to produce localized, single scatters within a single detector due to their rare and weakly interacting nature. The selection criteria for such events are as follows:

- (1) Each detector is equipped with four readout channels. Any valid energy deposition in a detector must be simultaneously recorded in all four channels. The total deposited energy (the sum over all four channels) must exceed 3 times the baseline resolution of the respective detector.
- (2) A coincidence time window of 200 μs is applied. Due to electronic limitations, phonon bouncing, pulse rise times, and the time separation between consecutive signals, this window represents a reasonable choice. If an energy deposition is detected in all four channels of a single detector, and no coinciding signal is observed in the other two detectors within this time window, the event is classified as a candidate single-scatter event.

Any event satisfying the above criteria is classified as a single-scatter event. Isolating single-scatter events enhances the sensitivity of the experiment to ALP signals by reducing background contributions. Since multiple-scatter events have already been excluded through the selection criteria, the combined set of single-scatter events from all detectors can be effectively treated as originating from a single detector, with a total mass equal to the sum of the individual detector masses.

B. Calibration

The energy spectrum for each detector is obtained by summing the optimal filter amplitudes from its four channels. Surface events can be easily ignored. Implementing surface event discrimination based on $\frac{A}{\text{amp}_{\text{ALL}}}$, which represents the ratio of the optimal filter amplitude in channel A to the sum of the amplitudes from all channels for each detector, rejects approximately 5% of events. This demonstrates that the calibration is not affected by surface events and that, to a good approximation, calibrating using all events or using only bulk events yields the same calibration function for each detector. Therefore, linear calibration for each detector is performed using an ^{55}Fe radioactive source, which emits characteristic x-rays of manganese: the dominant K_{α} line at approximately 5.89 keV and the weaker K_{β} line at approximately 6.49 keV. To demonstrate the performance of our detectors in resolving the two distinct peaks corresponding to the dominant x-ray emissions from the calibration source, Fig. 7 presents a zoomed-in view of the spectra around the main peaks for a 4 mm detector. As shown in this figure, this detector exhibits excellent capability in resolving the two distinct peaks from the radioactive source.

The overall baseline energy resolution for each detector after calibration, determined by fitting a Gaussian function to the sum of the noise spectrum of all channels, is found to be 39.91 ± 0.13 eV for the 4 mm detector, 107.3 ± 0.4 eV for detector 901, and 110.1 ± 0.4 eV for detector 903. The baseline resolution per channel for the 4 mm detector is approximately 35 eV, providing a 105 eV low-threshold

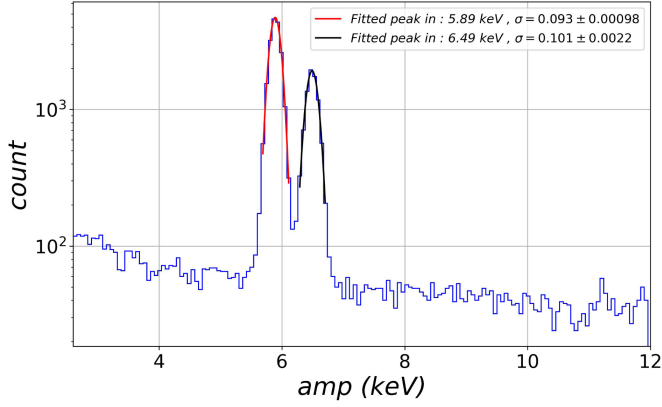


FIG. 7. The optimal filter (OF) amplitude spectra for a 4 mm detector.

detector while the upper detection limit due to saturation in 4 mm detector is between 75 to 80 keV. In the present analysis, the ALP-induced signal was treated as an unsmeared (delta-function-like) contribution within each energy bin. This approximation is justified based on a comparison between the detector energy resolution and the bin width used in the analysis.

The measured energy resolution of the detector, characterized by σ , ranges from 35 eV (baseline resolution per channel) to 101 eV (corresponding to the second calibration peak in Fig. 7). To properly match this resolution, an energy bin width of 0.1 keV was used for signal extraction. Selecting a bin width comparable to the detector resolution enhances the sensitivity of signal identification. In future work, particularly at high-flux reactors such as HFIR, we plan to adopt Gaussian convolution rather than a delta-function approach for modeling the signal shape, in order to fully exploit the detector's resolution, especially at lower energies.

Neglecting the smearing effect here introduces a minimal correction, estimated to be well below the statistical uncertainties of the measurement, and it does not affect the sensitivity results at the current level of precision. Therefore, the energy-dependent resolution function, $\sigma(E) = \sqrt{a^2 + b^2 E}$, where a accounts for baseline noise and b describes statistical broadening, was not applied in this work.

C. Experimental results

The reactor-on data were collected over a total of 59.5 hours across 21 days, between February and September 2022, while the reactor-off data were collected over 163.8 hours across 31 days during the same period. Figure 8 shows the resulting data collected during this run, with events identified as single-scatters shown in the top panel and multiple-scatter events shown in the bottom panel for two different phases. The multiple-scatter rate was calculated from the total event rate minus the single-scatter event rate.

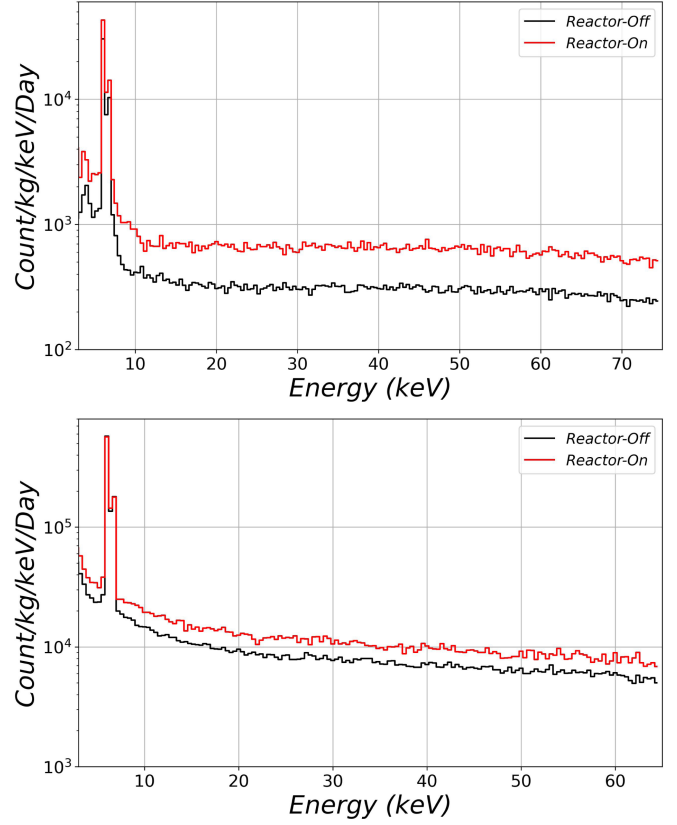


FIG. 8. Measured reactor-on and reactor-off count rates for single-scatter events (top) for the combination of three detectors and multiple-scatter events (bottom) for the 4 mm detector. These events are identified according to the definition of single-scatter events described in Sec. IV A.

D. ALP signal rate estimation

To calculate the ALP production rate, we convolve the photon flux with the Primakoff production cross section and the Compton scattering cross section. We adopted the reactor photon flux from the MINER experiment, as described in Ref. [38] and shown in Fig. 3. For projections involving the HFIR reactor, we assume that the integrated photon flux scales linearly with the thermal power of the reactor core. For simplicity, the reactor core material is approximated as pure thorium ($Z = 90$), representing an average effective atomic number for the core composition.

The produced ALPs then propagate through the shielding and surrounding materials. During propagation, ALPs may produce photons through decay in flight, the inverse Primakoff process, or inverse Compton scattering. The observable photon spectrum is the sum of these processes, which are calculated from Eqs. (3) and (5) (the equation for inverse Compton scattering is given in Ref. [31]). As an illustrative example, by integrating over the photon energy spectrum emitted from the reactor and substituting the relevant experimental parameters—including the detector area (A), the distance between the detector and the reactor core (l_d), and material-specific properties of the sapphire

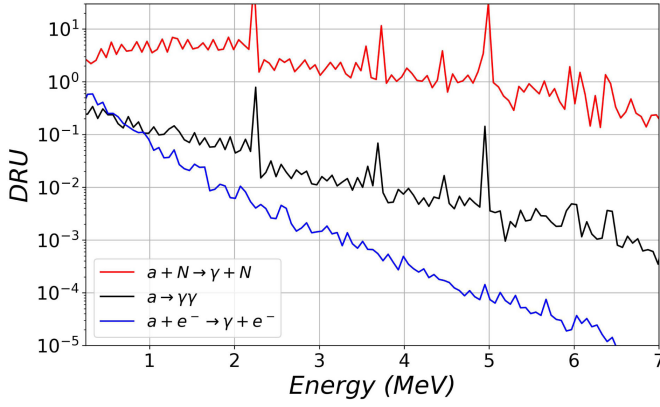


FIG. 9. The subsequent scatter and decay rates from ALPs in the detector volume are shown for individually chosen values of ($g_{a\gamma\gamma} = 10^{-3} \text{ GeV}^{-1}$, $g_{aee} = 10^{-5} \text{ GeV}^{-1}$) for a 10 keV ALP.

detector, such as the number of target atoms (N_T)—Fig. 9 shows the resulting photon spectrum for an assumed ALP mass of $m_a = 1 \text{ keV}$ and coupling constants $g_{a\gamma\gamma} = 10^{-3} \text{ GeV}^{-1}$ and $g_{aee} = 10^{-5} \text{ GeV}^{-1}$. These simulated results are in good agreement with the findings reported in Ref. [31], thereby validating the exclusion limits derived from our simulations.

The single-scatter background events measured during the reactor-off phase serve as a lower limit on the potential ALP-induced event rate. This limit is subsequently used to constrain the ALP signal rate, as expressed in Eqs. (3) and (5). Any genuine ALP signal must exceed the measured count rate of these single-scatter background events. In reactor-off mode, since there is no possibility of ALP production, any observed events are purely background.

E. Exclusion limits and projections

We calculate the projected upper limits on ALP couplings via a single-energy-bin analysis using $\kappa = \frac{N_s^2}{N_b}$ as a test statistic, where N_s and N_b are the integrated signal and background events, respectively. We calculate the upper limit on N_s with $\kappa = 4.61$ (corresponding to a 90% confidence level) and assuming a background given by the single-scatter event rate in reactor-off mode (shown in Fig. 8).

Figure 10 shows $g_{a\gamma\gamma}$ and g_{aee} as functions of the axion mass. In principle, for $m_a \lesssim 30 \text{ keV}$, the sensitivity of our setup is independent of the axion mass, resulting in a flat line for the axion-photon coupling. At higher masses, where the decay process becomes dominant, a strong dependence between the coupling and the mass emerges, leading to a downward-sloping sensitivity. For axion-electron coupling, by 1 MeV, we expect a flat line for the sensitivity, but due to the pair production after 1 MeV which opens a new decay channel, there is a sharp feature at this region. For higher masses, axion decay is too fast to be detected, which reduces sensitivity.

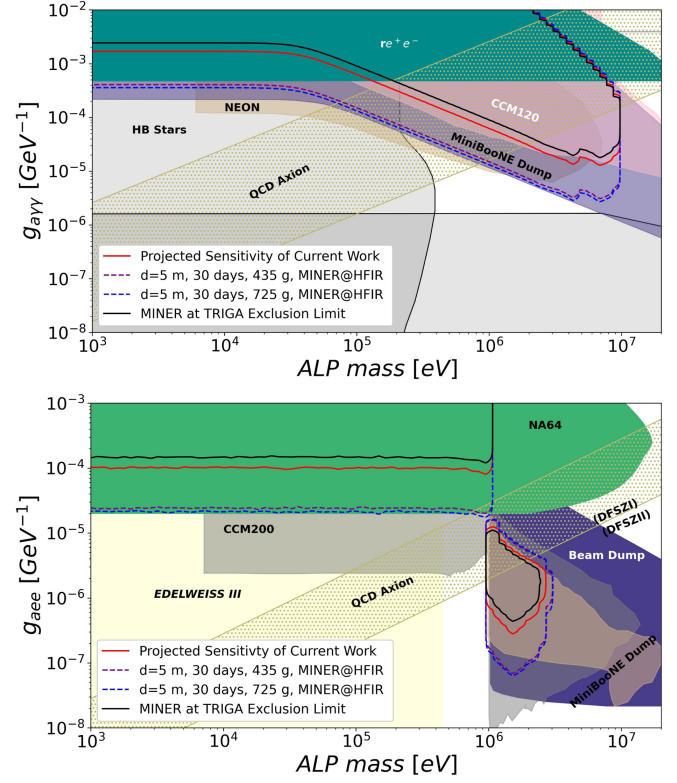


FIG. 10. Exclusion limits and projected sensitivity to ALP-photon couplings (top) and ALP-electron couplings (bottom) under various experimental conditions. The black curve shows the exclusion limit obtained from the current experiment, while the red curve corresponds to the achievable experimental sensitivity of the current setup with a lower background. The purple curve represents the projected sensitivity using the combination of all three detectors at the HFIR reactor, and the blue curve depicts the sensitivity achievable with five detectors (totaling 725 g) at the HFIR reactor.

Using reactor-on data and calculated N_s , we establish an exclusion limit using the fact that our experiment is sensitive to this ALP mass region. Figure 10 shows the resulting MINER at TRIGA exclusion limit, as well as projected exclusion limits at the 85 MW High Flux Isotope Reactor (HFIR).

The most remarkable aspect observed in Fig. 10, and a key advantage of our experiment, is the projected sensitivity achievable by scaling from the 1 MW h reactor to the 85 MW h High Flux Isotope Reactor (HFIR), positioned just 5 meters from the detector. As illustrated in Fig. 10(a), this upgrade would allow us to extend our reach into a previously unexplored region of the ALP parameter space (blue and purple curves) in the mass region up to 20 keV for $g_{a\gamma\gamma}$, significantly enhancing the potential for ALP discovery. For g_{aee} , Fig. 10(b) highlights a remarkable result: the extension of the current detector setup to five detectors—consisting of two detectors with a thickness of 4 mm and three detectors with a thickness of 1 cm, for a total mass of 725 g—would allow access to previously unexplored

parameter space, as indicated by the blue curve. Although this configuration was considered in the current experiment, due to technical issues we operated only with three detectors, whose analysis is presented in this work.

V. CONCLUSION

The MINER experiment, employing ultra-low-mass detectors with a low detection threshold and leveraging the high photon flux from reactors, has demonstrated sensitivity to ALPs comparable to much larger experiments. This setup presents an opportunity to probe previously unexplored regions in the ALP parameter space. Looking ahead, the current detector tower can be expanded to accommodate up to five detectors, increasing the total mass to approximately 725 g. This enhanced setup, in combination with the HFIR reactor at Oak Ridge National Laboratory as the primary photon source, has the potential to significantly improve the projected sensitivity of the experiment. Notably, this upgrade extends our reach deeper into the QCD axion parameter space, a key target for ALP search collaborations.

Other astrophysical constraints are derived from horizontal branch (HB) stars [41–46]. Laboratory-based

constraints on axionlike particles have been derived from beam-dump experiments, including MiniBooNE-DM and NEON [47,48]. As seen in Fig. 10, we would reach the experimentally unexplored astrophysical region just by using the high-flux photons created by the HFIR reactor and taking data for 30 days, which can extend our current results into this unexplored region. Since this work is limited to the mass range of 3 keV to 10 MeV, we plan to extend our search to the sub-3 keV region in future investigations.

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DATA AVAILABILITY

The data are not openly available but can be available for the proper request.

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