

New Directions for Axionlike Particle Searches Combining Nuclear Reactors and Haloscopes

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In this Letter, we propose reactoscope, a novel experimental setup for axionlike particle (ALP) searches. Nuclear reactors produce a copious number of photons, a fraction of which could convert into ALPs via Primakoff process in the reactor core. The generated flux of ALPs leaves the nuclear power plant and its passage through a region with a strong magnetic field results in the efficient conversion to photons that can be detected. Such magnetic field is the key component of axion haloscope experiments. Adjacent nuclear reactor and axion haloscope experiments exist in Grenoble, France. There, the Institut Laue-Langevin research reactor is situated only ~ 700 m from GrAHal, the axion haloscope platform designed to offer several volume and magnetic field (up to 43 T) configurations. We derive sensitivity projections for photophilic ALP searches with the institute and GrAHal, and also scrutinize analogous realizations, such as the one comprising the Axion Solar Telescope experiment at CERN and the Bugey nuclear power plant. The results that we obtain complement and extend the reach of existing laboratory experiments, e.g., the light-shining-through-walls experiment. While the derived sensitivities are not competitive when compared to the astrophysical limits, our analysis is free from the assumptions associated with those limits.

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Introduction.—The standard model (SM) of particle physics is an extremely successful theory that has described with astonishing accuracy most observed phenomena in high energy physics. Despite its predictive power, the model presents some issues, both at the theoretical level in the form of fine-tuned parameters and at the experimental level, with measurements directly incompatible with SM predictions. These open problems allow us to investigate new physics realizations capable of addressing the aforementioned shortcomings.

In this Letter, we will focus on one particular beyond the SM realization: axionlike particles (ALPs) (denoted as a), which have properties similar to those of QCD axions with the notable difference in the fact that the particle’s mass and its decay constant are treated as independent parameters. Regarding experimental efforts, see, e.g., [1–3] for a broad summary of ALP constraints from terrestrial experiments as well as cosmological and astrophysical probes.

We will focus on the following interaction of ALPs with the SM:

$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4}g_{a\gamma\gamma}aF^{\mu\nu}\tilde{F}_{\mu\nu}, \quad (1)$$

where $g_{a\gamma\gamma}$ is the interaction strength (in units of GeV^{-1}) and $F^{\mu\nu}$ is the field strength tensor of the electromagnetic field, where $\tilde{F}_{\mu\nu} = \frac{1}{2}F^{\alpha\beta}\epsilon_{\alpha\beta\mu\nu}$ is its dual, with $\epsilon_{1230} = 1$.

We propose a new realization, dubbed “reactoscope,” for testing ALPs that interact via Eq. (1). Namely, we put forward a possibility of combining two different experimental facilities: ALPs are produced in nuclear reactors via a scattering process that occurs through the interaction in Eq. (1) and, due to the same $\gamma - a$ coupling, ALPs can convert back to photons in a magnetic field. An experimental realization involving the strong magnetic field is provided in the haloscope experiments that utilize resonant cavities [4]. Such cavities are used for resonant conversion of light axion dark matter particles; the conversion is maximized when axion mass matches the resonant frequency [5]. In contrast, the cavities are not useful within our setup since, for reactor ALPs [$\mathcal{O}(\text{MeV})$ energy], the resonant condition cannot be met. However, the strong magnetic field from such experiments is crucial for the method proposed in this Letter.

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The realization with the nuclear reactor and the resonant cavity experiment in proximity to each other exists in Grenoble, France, where the Institut Laue-Langevin (ILL) research reactor is placed around 700 m from GrAHal, the axion haloscope platform. GrAHal will be able to run detectors of different sizes and designs, with an axion and ALP mass sensitivity in the range of 1.25 to 125 μeV [6–8]. One of its main components is the Grenoble hybrid magnet. This magnet can generate a magnetic field up to 43 T within a 34 mm diameter aperture. Another configuration will allow for the production of 17.5 T in a 375 mm diameter aperture and 9.5 T in an 812 mm diameter bore. Additionally, several superconducting coils capable of generating magnetic fields up to 20 T within a 50 mm diameter will allow for the simultaneous operation of multiple haloscopes. We are proposing an experiment that should not interfere with the scheduled programs of ILL and GrAHal. Additionally, such a realization would by no means require a large financial commitment given that almost all the required components are already operating. Additionally, we should also stress that ILL is equipped with several strong magnets that can also be utilized for axion searches; such magnets are presently used in different branches of physics, primarily involving neutrons [9,10]. A similar realization to ILL-GrAHal that will also be considered in this Letter is the combination of the Bugey nuclear power plant (near the city of Lyon, France) and CERN Axion Solar Telescope (CAST) helioscope [11,12] based at CERN.

Regarding the production of ALPs in nuclear reactors, let us bring up Refs. [13,14] where the authors studied detection of ALPs via scattering or decay in neutrino experiments (for other ALP searches, see, e.g., [15–18]). In this Letter we are instead focused on conversion in the magnetic field and we identify regions in the parameter space that exceed sensitivity projections derived in [13,14]. Furthermore, let us also point out Ref. [19] where the authors considered ALP production in accelerator experiments and a subsequent detection through the conversion in a magnetic field, where the latter can be achieved for instance by reusing, e.g., CAST magnets. While we consider such a proposal appealing, we stress that the advantage of the setup proposed in this Letter is that the components for both ALP production and detection (adjacent nuclear reactor and magnetic field) are already present and operating at the aforementioned sites.

In the remainder of the Letter, we focus on computing sensitivity projections for the proposed experimental setup.

ALP production at reactors.—Nuclear reactors are a powerful source of neutrons, neutrinos, and photons and it is the latter that are relevant for the production of ALPs, given Eq. (1). The photon fluxes in the reactor core vary across different reactor facilities as they depend on the fuel and the configuration of the core, which we treat as monolithic uranium. In the center of our interest is the

ILL reactor for which, to the best of our knowledge, the detailed photon flux estimation is not publicly available. Hence, as a proxy, we will use the analysis for the FRJ-1 research reactor [20] that also used ^{235}U for the nuclear fission. Such a strategy was also employed recently in the literature in the context of both dark photon [21,22] and ALP [14] production.

We parametrize the photon flux, arising both from fission itself and subsequent beta decays, in the core as [14,20]

$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{0.58 \times 10^{21}}{\text{MeVs}} \left(\frac{P}{\text{GW}} \right) e^{-1.1 \frac{E_\gamma}{\text{MeV}}}, \quad (2)$$

where P is the thermal power of the reactor and E_γ is the photon energy. The ILL reactor has a thermal power of 58 MW, while the commercial Bugey power plant has a thermal power of roughly 3.6 GW. We note that Eq. (2) has uncertainties. While it is beyond the scope of this Letter to perform a detailed simulation for the particular reactor, we have compared this parametrization with the simulation results from Ref. [13]. We found that the two integrated photon fluxes differ roughly by a factor of 2. Given the $g_{a\gamma\gamma}^4$ dependence of the event rate (to be shown later), the factor of 2 uncertainty in the flux would lead only to a 20% ($2^{0.25} \simeq 1.2$) correction in the sensitivity projections for $g_{a\gamma\gamma}$.

Photons in the reactor core can interact with the nuclear fuel, namely ^{235}U . In most cases, this interaction would lead to absorption or scattering of a photon; however, once in a while a photon can produce an ALP via Primakoff scattering, i.e., $N + \gamma \rightarrow N + a$, where N is an atomic nucleus.

The differential cross section for this process reads [23]

$$\begin{aligned} \frac{d\sigma_{\text{Prim}}}{dt} &= 2\alpha Z^2 |F(t)|^2 g_{a\gamma\gamma}^2 M_N^4 \\ &\times \frac{m_a^2 t (M_N^2 + s) - m_a^4 M_N^2 - t((M_N^2 - s)^2 + st)}{t^2 (M_N^2 - s)^2 (t - 4M_N^2)^2}, \end{aligned} \quad (3)$$

where t and s are the Mandelstam variables, Z , M_N , and m_a are the atomic number, mass of the ^{235}U , and ALP mass, respectively. Further, α is the fine structure constant and $F^2(t)$ is the nuclear form factor; see, e.g., [24,25] for the definitions. In passing, let us also stress that the Primakoff process can occur via scattering on electrons as well ($\gamma e^- \rightarrow a e^-$); however, scattering on ^{235}U strongly dominates because of the Z^2 enhancement in the cross section. Notice that nuclear reactors emit photons with energies of at most $\mathcal{O}(10)$ MeV, whereas the mass of ^{235}U is $M_N \sim 200$ GeV. This implies that the energy of the photon that scatters on nucleus and the energy of ALP that is produced in such an interaction approximately coincide; we therefore take $E_\gamma = E_a$ in order to simplify the calculations.

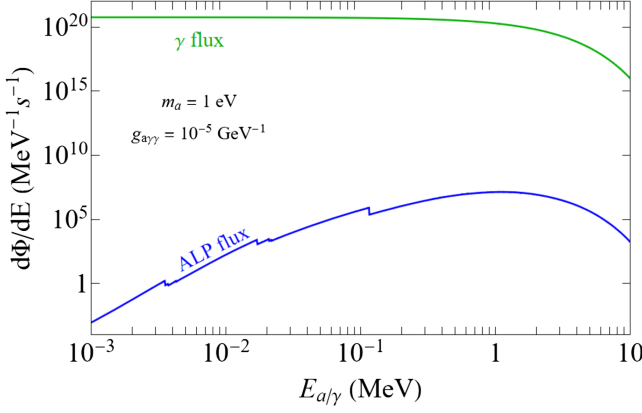


FIG. 1. Comparison of the γ flux in Eq. (2) and ALP flux in Eq. (4). Reactor thermal power is taken as 1 GW.

Then, the ALP flux at the production site reads

$$\frac{d\Phi_a^0}{dE_a} = \frac{\sigma_{\text{Prim}}(E_a)}{\sigma_{\text{tot}}(E_a)} \frac{d\Phi_\gamma(E_a)}{dE_a}, \quad (4)$$

where σ_{tot} is the total cross section for the scattering of a photon with ^{235}U , including SM and ALP contributions. We assume that the photon is extinguished in each interaction, which implies an underestimation in the photon (and consequently ALP) flux at low energies. This means that our calculations are conservative. Similarly as in [14], we extracted σ_{tot} from [26]. In Fig. 1, we make a comparison between the photon and ALP fluxes at the production site. The latter is suppressed due to small $\sigma_{\text{Prim}}/\sigma_{\text{tot}}$.

The produced ALPs will travel a certain distance, and we need to take into account both their survival probability and the spatial dilution of the flux. Regarding the former, given the interaction in Eq. (1), ALPs can decay to two photons and we are interested in ALPs that do not decay before reaching distance D from the reactor core. The decay rate reads

$$\Gamma(a \rightarrow \gamma\gamma) = \frac{g_{a\gamma\gamma}^2}{64\pi} m_a^3. \quad (5)$$

The lifetime in the laboratory frame is hence $\tau = (E_a/m_a)\sqrt{1 - m_a^2/E_a^2}\Gamma^{-1}(a \rightarrow \gamma\gamma)$ and the survival probability reads $P_{\text{surv}} = \text{Exp}[-D/(c\tau)]$.

Regarding the latter, for nuclear reactors we assume an isotropic production as a conservative estimate [27]. Given the above, we are now able to express ALP flux at the distance D from the core as

$$\frac{d\Phi_a}{dE_a} = \frac{P_{\text{surv}}}{4\pi D^2} \frac{\sigma_{\text{Prim}}(E_a)}{\sigma_{\text{tot}}(E_a)} \frac{d\Phi_\gamma}{dE_a}. \quad (6)$$

ALP detection.—Let us now turn our attention toward the detection. Here, we envision $a \rightarrow \gamma$ conversion in the

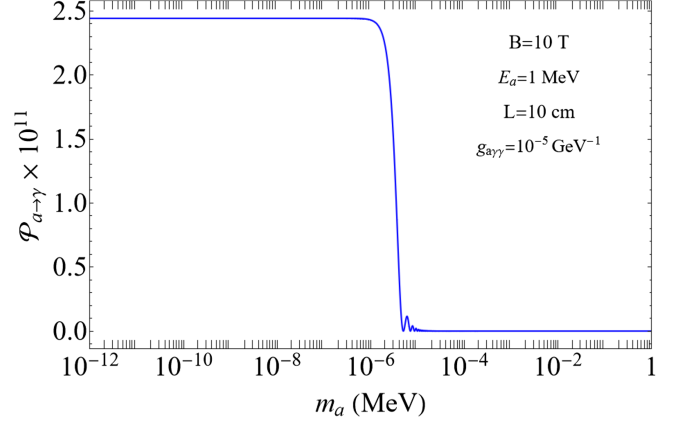


FIG. 2. $\mathcal{P}_{a \rightarrow \gamma}$ as a function of m_a .

magnetic field, in the similar spirit as it is done at helioscopes like CAST [11,12]. The conversion probability of an ALP that travels across the distance L immersed in a magnetic field B into a photon reads [28–30]

$$\mathcal{P}_{a \rightarrow \gamma} = \left(\frac{g_{a\gamma\gamma} B}{q} \right)^2 \sin^2 \left(\frac{qL}{2} \right), \quad (7)$$

with $q = \sqrt{(m_a^2/(2E_a))^2 + (g_{a\gamma\gamma} B)^2}$. For small m_a and $g_{a\gamma\gamma}$, which will appear to represent the parameter space of our interest, it can be shown that $\mathcal{P}_{a \rightarrow \gamma} \approx (g_{a\gamma\gamma} B L / 2)^2$; namely, the dependence on q drops due to $\lim_{x \rightarrow 0} (\sin^2 x / x^2) = 1$. $\mathcal{P}_{a \rightarrow \gamma}$ is shown in Fig. 2; note that the plateau in the small m_a region corresponds to the parameter space in which this approximation is applicable.

Finally, we are ready to obtain the number of photons produced in the magnetized region by convoluting Eq. (7) with the flux in Eq. (6). This reads

$$N_\gamma = T\pi R^2 \int \frac{d\Phi_a}{dE_a}(E_a) \mathcal{P}_{a \rightarrow \gamma} dE_a, \quad (8)$$

where we also included the exposure time, T , and the cross-sectional area of the magnetized region (cavity), which we assume to be a cylinder of radius R and length L . Equation (8) is the expression based on which we will discuss sensitivity projection estimates. In passing, let us mention that there is yet another possibility for the detection; ALP can, in principle, decay into two photons within the cylinder; however, since $D \gg L$, the probability for the decay within the magnetized volume is negligible when compared to the $\mathcal{P}_{a \rightarrow \gamma}$.

Experimental setup and sensitivities.—Before presenting the main results, let us discuss the envisioned experimental setup and background events. For a successful measurement, a photon detection system should be placed right behind the magnetized region. Regarding detectors, one option is to use inorganic scintillators, e.g., NaI[Tl], LaBr3

(Ce), with the respective efficiencies in the ballpark of $\mathcal{O}(\%)$ for MeV photon energies [31,32]. Another option is to use the same material that CAST installed for solar axion searches, CdWO₄, and for this scintillator crystal, the detection efficiencies are in the ballpark of 30% to 40% [33,34]. We have included these in our calculations.

We will now make conservative background estimates based on CAST studies for the performance of CdWO₄ detector in search for axions with MeV energy [35]. In [35], after applying the cuts, the irreducible background rate is about one event per second. Given the period of $T = 3$ y that we will typically use in our sensitivity studies, this amounts to $\sim 10^8$ background events. To get the exclusion at 1σ level, we would then require the number of signal events to be approximately equal to $\sqrt{10^8}$. Given that the number of ALP-induced photon events scales with $g_{a\gamma\gamma}^4$ [2 powers of $g_{a\gamma\gamma}$ in Eq. (3) and another two in Eq. (7)], this conservative estimate would lead to the reduction of the sensitivity in $g_{a\gamma\gamma}$ by 1 order of magnitude compared to the ideal case with no backgrounds [where $\mathcal{O}(1)$ signal events suffice for the discovery]. We should still stress that [35] dates back 15 years; to the best of our knowledge, there are no more recent studies by CAST on MeV energy solar axion searches, so we are not aware of any more recent improvements with regard to the CdWO₄ detectors. However, in this time period, CAST was able to reduce backgrounds in one of their x-ray detectors, Micromegas [36], (used for lower energy, namely keV axion searches) by 2 orders of magnitude [37]. Assuming such background reduction were achievable for the CdWO₄ detector as well, the sensitivity would be only a factor of ~ 5 worse than in the zero background limit. Note also that the cross-sectional area of CAST is 14.5 cm² and for one of the proposed GrAHal [6,8] configurations we consider the realization with $R = 1.7$ cm, which further improves the situation, given the scaling of the background events with R^2 .

The main backgrounds considered above arise from cosmic rays and radioactivity of the detector material. In addition to that, the experimental setup we propose in this Letter may also suffer from background events stemming from the nearby nuclear reactor. Let us, hence, discuss particles that are emitted from the power plants. Photons, which we use to produce ALPs in the reactor core, are effectively absorbed and do not reach the detector. However, neutrons from reactors can travel greater distances and in collision with nuclei (in or near the detector) they could induce the appearance of secondary photons in the detection system. Such background was already under consideration for the STEREO experiment [38] near ILL. In Ref. [39], it was shown that neutron-induced background can be effectively suppressed with extra shielding. Reactors are also abundant sources of neutrinos; however, the size of the proposed experimental configuration is such that, given the small neutrino cross sections, neutrino-induced background events are not expected.

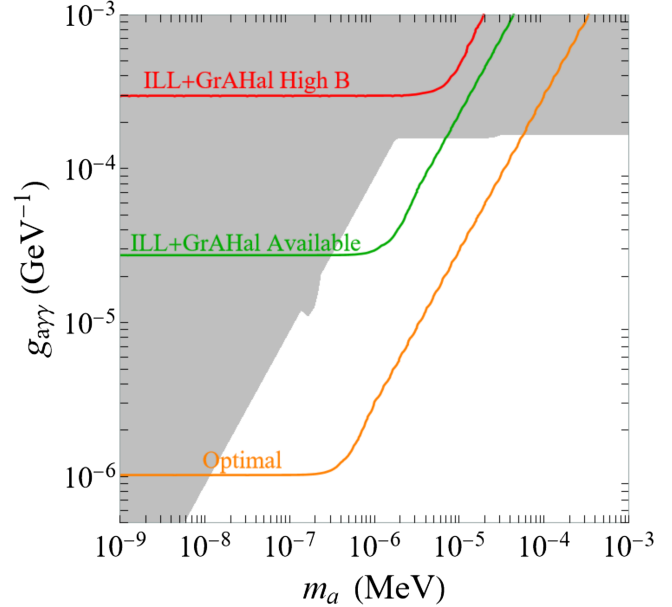


FIG. 3. Sensitivity projections in the $m_a - g_{a\gamma\gamma}$ parameter space for the considered scenarios where various combinations of reactors and magnets are employed. In gray, we superimpose constraints from existing laboratory experiments, adopted from [42].

Given the discussion above, we do not expect reactor-related backgrounds. This can also be verified at particular reactor by comparing reactor-on versus reactor-off photon rates; see Ref. [40].

In what follows we will show 95% confidence level sensitivity projections ($\chi^2 = 3.841$) obtained by solving Eq. (8), assuming optimistically that all the backgrounds can be removed. Note that, as discussed above, the irreducible backgrounds would in the worst case lead to a factor of few reductions in the sensitivity for $g_{a\gamma\gamma}$.

We have considered several different possible scenarios.

First, ALP production at ILL, photon detection at GrAHal, with B and R taken from the *last* line of Table I in [6] ($B = 9.5$ T, $R = 40$ cm) and $L = 80$ cm. In Fig. 3, this scenario is denoted as “ILL + GrAHal Available” as the magnetic field matches the vanilla setup. The sensitivity is shown by the green line in Fig. 3.

Second, ALP production at ILL, photon detection at GrAHal, with B and R taken from the *first* line of Table I in [6] ($B = 43$ T, $R = 1.7$ cm) and $L = 3.4$ cm [7,8]. In Fig. 3, this scenario is denoted as “ILL + GrAHal High B”; indeed it was shown that the setup with $B > 40$ T is being commissioned at GrAHal. For both this and the previous scenario $D = 700$ m and we take $T = 3$ y. The sensitivity is shown by the red line in Fig. 3.

Third, ALP production at ILL and detection with ILL magnets [9,10] at distance of $D = 50$ m. With an ILL magnet of $B = 10$ T, $L = 318$ mm, and $R = 19.5$ mm [10] we find the reach in $g_{a\gamma\gamma}$ to be reduced by roughly a factor of 2 with respect to “ILL + GrAHal Available” projection.

Fourth, ALP production at Bugey and detection with CAST at CERN. The distance between Bugey and CERN is $D \sim 75$ km. Further, $B = 9$ T, $L \approx 9$ m, and $R = \sqrt{14.5/\pi\text{cm}^2}$ [12]. CAST has been taking data approximately 3 h per day (sunrise and sunset) but, if oriented and fixed in the direction of the Bugey reactor, it could be operative throughout the whole day. This kind of realization is imaginable since CAST is approaching its end of data taking and will be superseded by BabyIAXO and ultimately IAXO [41]. The sensitivity that we found for this scenario is $g_{\alpha\gamma\gamma} \gtrsim 10^{-4}$ GeV $^{-1}$, meaning that a stronger and/or closer magnet would be required to surpass existing laboratory constraints.

We also consider the “Optimal” configuration where we pair the nuclear power plant with the largest available thermal power, Kashiwazaki-Kariwa power plant near Tokyo ($P \simeq 8.2$ GW), and BabyIAXO magnet at the distance of $D \sim 50$ m. We adopt $R = 35$ cm, $L = 10$ m, $B = 2$ T [41] and assume $T = 10$ y of running. The sensitivity is shown by the orange line in Fig. 3.

The scenario “ILL + GrAHal Available” appears particularly promising; it exceeds laboratory constraints (shown in gray in Fig. 3) for $m_a \gtrsim 10^{-1}$ eV. Despite the smaller B in that case, R is much larger than in “ILL + GrAHal High B” and the leading effect hence stems from the angular acceptance. For “ILL + GrAHal Available,” the ALP mass for which sensitivity starts ceasing is smaller than for the “ILL + GrAHal High B” combination. This can be understood from the ALP conversion formula given in Eq. (7); sensitivity starts dropping for $m_a^2 L/E_a \gtrsim 1$ and since L is much larger for the available realization, this feature appears at smaller values of m_a .

Finally, the results for the most promising scenario, in which we paired the world’s strongest nuclear reactor and the BabyIAXO magnet, are shown by the “Optimal” sensitivity in Fig. 3. Here, both large ALP flux and strong B field are at work making the sensitivity reach $g_{\alpha\gamma\gamma} \approx 10^{-6}$ GeV $^{-1}$. One can infer a large portion of the yet uncovered parameter space that can be probed. The astrophysical and cosmological constraints are not included in the shown constraints. While, admittedly, they would dominate, ALP production in such scenarios can be strongly suppressed; see, e.g., [43–46], the studies motivated by the PVLAS anomaly [47].

Conclusion.—In this Letter, we have proposed marrying two very different facilities in order to search for ALPs. Provided that ALPs interact with photons, they can be copiously produced at nuclear reactors via Primakoff scattering. Through the same interaction term in the Lagrangian, ALPs can convert back to photons in the magnetic field. Grenoble is a great location for conducting such an experiment since it has ILL research reactor and GrAHal, a haloscope platform with strong magnetic field,

at only 700 m from each other. In addition to that, we also studied several other interesting possibilities, namely combining the commercial Bugey power plant and CAST experiment at CERN, as well as the world’s strongest nuclear reactor with the next generation axion helioscope. The sensitivity projections found in this Letter are, for the ALP mass range $m_a \in [10^{-2}, 10]$ eV, stronger than the existing laboratory constraints. Given this exciting physics potential and the low-cost aspect of the experiment, we envision this Letter to initiate a brand new program for ALP searches that may potentially lead to new discoveries.

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