PROCEEDINGS OF SCIENCE

Probing axion-like particles with reactor neutrino experiments

D. Aristizabal Sierra,[a] V. De Romeri,[b] L. J. Flores[c] and D.K. Papoulias[d,*]

[a] *Universidad Técnica Federico Santa María - Departamento de Física Casilla 110-V, Avda. España 1680, Valparaíso, Chile*

[b] *Instituto de Física Corpuscular, CSIC/Universitat de València, Calle Catedrático José Beltrán, 2 E-46980 Paterna, Spain*

[d] *ITecnológico Nacional de México/ITS de Jerez, C.P. 99863, Zacatecas, México*

[d] *Department of Physics, University of Ioannina GR-45110 Ioannina, Greece*

E-mail: daristizabal@ulg.ac.be, deromeri@ific.uv.es, ljflores@jerez.tecnm.mx, d.papoulias@uoi.gr

Reactor neutrino experiments provide a rich environment for the study of axionlike particles (ALPs). Using the intense photon flux produced in the nuclear reactor core, these experiments have the potential to probe ALPs with masses below 10 MeV. We explore the feasibility of these searches by considering ALPs produced through Primakoff and Compton-like processes as well as nuclear transitions. These particles can subsequently interact with the material of a nearby detector via inverse Primakoff and inverse Compton-like scatterings, via axio-electric absorption, or they can decay into photon or electron-positron pairs. We demonstrate that reactor-based neutrino experiments have a high potential to test ALP-photon couplings and masses, currently probed only by cosmological and astrophysical observations, thus providing complementary laboratory-based searches. We furthermore show how reactor facilities will be able to test previously unexplored regions in the ~MeV ALP mass range and ALP-electron couplings of the order of $g_{aee} \sim 10^{-8}$ as well as ALP-nucleon couplings of the order of $g_{ann}^{(1)} \sim 10^{-9}$, testing regions beyond TEXONO and Borexino limits.

**** The 22nd International Workshop on Neutrinos from Accelerators - NuFaCT 2021 ****
**** 6 - 11 September, 2021 ****
**** Cagliari, Italy ****

*Speaker

© Copyright owned by the author(s) under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (CC BY-NC-ND 4.0).

PoS(NuFact2021)090

1. Introduction

In recent years, there is a rapidly developing physics program aiming at measuring coherent elastic neutrino-nucleus scattering (CEνNS) using reactor neutrinos, which offers exciting possibilities to explore physics beyond the SM. In the present work, we focus on Axionlike particles (ALP) i.e. pseudoscalars that feebly couple to the SM particles such as photons, electrons and nucleons according to

$$\mathcal{L} = -\frac{1}{4}\, g_{a\gamma\gamma}\, a F_{\mu\nu} \widetilde{F}^{\mu\nu} - i g_{aee} a\, \bar{e}\gamma_5 e - i a \bar{n}\gamma_5 \left(g^{(0)}_{ann} + \tau_3 g^{(1)}_{ann} \right) n \,, \tag{1}$$

and we investigate the feasibility and extent of such searches by including leading ALP production and detection mechanisms at reactor neutrino experiments. In addition to nuclear magnetic transitions, considered by previous reactor searches, here we take into account additional ALP production mechanisms such as Compton-like and Primakoff scattering. We furthermore consider detection through their inverse processes as well as via axio-electric absorption and ALP decays to diphoton and electron pairs. We find that such facilities are favorable locations for probing ALPs in the mass range $(1 - 10^7$ eV).

Our analysis follows minimal ALP assumptions in the sense that it considers only those processes that allow production and detection through the same ALP-SM coupling, the exception being production through nuclear de-excitation. In this case we consider detection through either ALP-photon or ALP-electron couplings, following to a large extent the analysis carried out by TEXONO in Ref. [1]. Rather than sticking to a particular CEνNS reactor-based experiment, our analysis is formulated as generic as possible, and therefore being representative of what current or near-future technologies could achieve.

2. ALPs production and detection mechanisms at reactors

Photons are abundantly produced in nuclear power plants. Processes responsible for γ emission are fission, decay of fission products, capture processes in fuel and other materials, inelastic scattering in the fuel, and decay of capture products. The prompt photon flux can be described by

$$\frac{\mathrm{d}\Phi_{\gamma'}}{\mathrm{d}E_{\gamma'}} = \frac{5.8\times 10^{17}}{\mathrm{MeV}\cdot \mathrm{sec}} \left(\frac{\mathrm{P}}{\mathrm{MW}}\right) e^{-1.1\, E_{\gamma'}/\mathrm{MeV}} \,, \tag{2}$$

where P is the reactor power in MW, an approximation originally derived from an analysis of γ radiation in the FRJ-1 research reactor [2]. Once produced, these photons can interact with the fuel material which we assume to be ^{235}U. This choice is motivated by the fact that most of the reactor experiments our analysis applies to, use this uranium isotope (totally or partially) as fuel material.

For a continuous photon flux[1] the differential ALP flux $\mathrm{d}\Phi_{\mathrm{ALP}}/\mathrm{d}E_a$ (a is the ALP energy) is then calculated from the master formula

$$\frac{\mathrm{d}\Phi_{\mathrm{ALP}}}{\mathrm{d}E_a} = \mathcal{P}_{\mathrm{surv}} \int_{E_{\gamma',\mathrm{min}}}^{E_{\gamma',\mathrm{max}}} \frac{1}{\sigma_{\mathrm{Tot}}} \frac{\mathrm{d}\sigma^{\mathrm{prod}}_{\mathrm{ALP}}}{\mathrm{d}E_a}(E_{\gamma'}, E_a)\, \frac{\mathrm{d}\Phi_{\gamma'}}{\mathrm{d}E_{\gamma'}}\; dE_{\gamma'} \,, \tag{3}$$

[1]For the case of a monochromatic photon flux from nuclear dexcitation see Ref. [1].

PoS(NuFact2021)090

where $\sigma_{\rm Tot} = \sigma_{\rm SM} + \sigma_{\rm ALP}^{\rm prod}$, with the SM cross section being $\sigma_{\rm SM} = \sigma_{\rm R} + \sigma_{\rm C} + \sigma_{\rm PE} + \sigma_{e-\rm pair}$, while the ALP production cross section $\sigma_{\rm ALP}^{\rm prod}$ is either $\sigma_{\gamma N \to a N}$ or $\sigma_{\gamma e^- \to a e^-}$ corresponding to Primakoff or Compton scattering, respectively (see Refs. [3, 4]). The ALP survival probability, $\mathcal{P}_{\rm surv}$ assuring that the ALP flux reaches the detector, can be cast as [5]

$$\mathcal{P}_{\rm surv} = e^{-L E_a / |\vec{p}_a| \tau}\,, \tag{4}$$

where L refers to the distance between the reactor and detector and τ to the ALP lifetime in the fixed target frame, determined in turn by the ALP total decay width: $\tau^{-1} = \Gamma \times m_a/E_a$, while the respective Primakoff- and Compton-like decays read

$$\Gamma_{a \to 2\gamma} = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}, \qquad \Gamma_{a\to e^+ e^-} = \frac{g_{aee}^2 m_a}{8\pi}\sqrt{1 - 4\frac{m_e^2}{m_a^2}}\,. \tag{5}$$

Then, the differential event rate at reactor experiment consists of two terms, one from the inverse-Primakoff or inverse-Compton scattering and another one from the corresponding ALP decays

$$\frac{d\mathcal{N}_{\rm Tot}}{dE_a} = \frac{d\mathcal{N}_{\rm scat}}{dE_a} + \frac{d\mathcal{N}_{\rm decay}}{dE_a}\,. \tag{6}$$

The first term results from a convolution of the ALP flux and the ALP-photon differential cross section[2], namely

$$\frac{d\mathcal{N}_{\rm scat}}{dE_a} = m_{\rm det}\frac{N_T \Delta t}{4\pi L^2}\int \frac{d\Phi_{\rm ALP}}{dE_a}\frac{d\sigma_{\rm ALP}^{\rm det}}{dE_\gamma}\, dE_\gamma\,, \tag{7}$$

where $N_T = N_A/m_{\rm molar}$ with $N_A = 6.022 \times 10^{23}/{\rm mol}$ and $m_{\rm molar}$ the target nuclei molar mass in kg/mol, while Δt stands for the data-taking time and $m_{\rm det}$ refers to the detector mass in kg. The ALP decay-induced events can be evaluated from from second term in Eq. (6) which reads

$$\frac{d\mathcal{N}_{\rm decay}}{dE_a} = \frac{\mathcal{A}\Delta t}{4\pi L^2}\frac{d\Phi_a^{\rm P}}{dE_a}\mathcal{P}_{\rm decay}, \qquad \mathcal{P}_{\rm decay} = 1 - e^{-L_{\rm det}E_a/|\vec{p}_a|\tau}\,, \tag{8}$$

where $P_{\rm decay}$ accounts for the probability that the decay occurs within the detector, while $L_{\rm det}$ stands for the detector thickness and $\mathcal{A} = L_{\rm det}^2$ denotes the detector transverse area. Let us finally note that for interactions with electrons, an additional contribution to the event rate is expected due to the axio-electric effect (for details, see Ref. [7])

$$\frac{d\mathcal{N}_{\rm axio}}{dE_a} = m_{\rm det}\frac{N_T\Delta t}{4\pi L^2}\frac{d\Phi_{\rm ALP}}{dE_a}\,\sigma_{\rm axio}(E_\gamma, E_a)\,. \tag{9}$$

3. Results and discussion

Motivated by the current CEνNS experimental program, which aims at observing CEνNS induced by reactor neutrino fluxes using various low-threshold technologies, we have analyzed the prospects for detection of ALPs in such experiments. We have assumed a 10 kg germanium detector, which we regard as representative of current (CONUS [8]) or near-future CEνNS experiments

[2]For ALP detection via inverse-Primakoff or inverse-Compton scattering $\sigma_{aN\to\gamma N}$ or $\sigma_{ae^-\to\gamma e^-}$ the associated differential cross sections $d\sigma_{\rm ALP}^{\rm det} dE_\gamma$ are taken from Refs. [3, 6].

PoS(NuFact2021)090

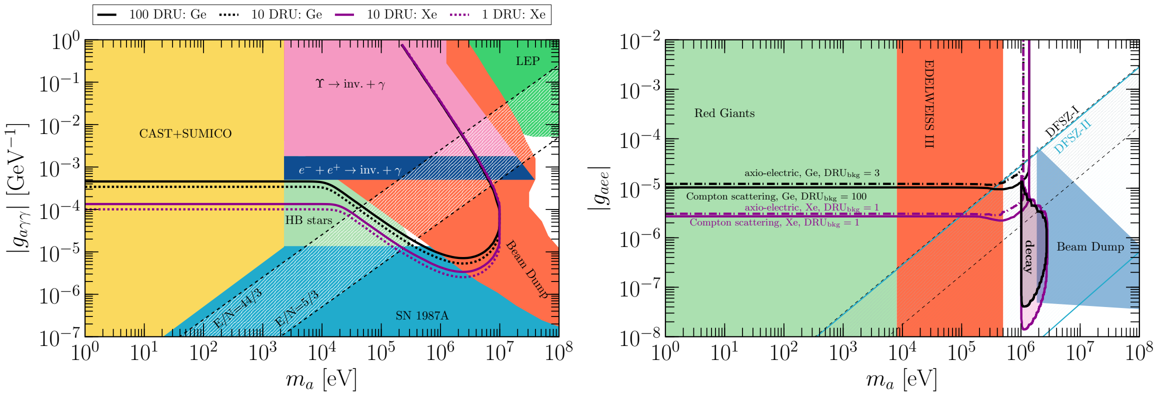

Figure 1: Current and future sensitivities at 90%CL on the photon-ALP (left) and electron-ALP (right) couplings for different backgrounds along with relevant laboratory, astrophysical and cosmological limits that apply in the region of interest (see the text). Figure adapted from Ref. [7].

(including MINER [9], Ricochet [10], νGeN [11] and TEXONO [12]). We have also explored future capabilities of next generation experiments, assuming a ton-scale xenon detector. In this work, we restrict our selves by assuming a non-vanishing ALP coupling at a time i.e. $g_{a\gamma\gamma}$ or g_{aee} (results with combined couplings of the form $g_{a\gamma\gamma} \times g_{ann}$ or $g_{aee} \times g_{ann}$ are presented in Ref. [7]). Hence, for probing $g_{a\gamma\gamma}$ we consider ALP production through Primakoff-like scattering and detection through inverse Primakoff-like as well as decay into a $\gamma-$pair final states. Regarding g_{aee}, we include production through Compton-like scattering and detection through inverse Compton-like, axio-electric as well as $e-$pair production in e field and decay into an electron-positron pair.

In the left and right panel of Fig. 1, we present the calculated 90%CL sensitivities in the ALP mass-coupling parameter space. Black (purple) contours correspond to sensitivities achievable with ongoing or near-future (next generation) experiments. Solid (dotted) contours refer to sensitivities under the assumption of a background rate of 100 DRU (10 DRU) for ongoing or near-future experiments, while to 10 DRU (1 DRU) for a next generation setup. For completeness we show as well the region covered by QCD axion models. The extracted sensitivities are also confronted to existing constraints from laboratory and astrophysical searches. As can be seen, for models with dominant $g_{a\gamma\gamma}$ coupling, these experiments will probe a region in the ALP mass range around 1 MeV, presently constrained only by cosmological observations. Moreover, since reactor searches will cover regions currently constrained by CAST+SUMICO, SN 1987A and HB stars cooling arguments, they can also potentially test ALPs environment-dependent properties in stellar media. For ALP models with dominant ALP-electron coupling, reactor searches will probe ALP masses in the range $[5, 20] \times 10^5$ eV and ALP-electron couplings extending down to $g_{aee} \sim 10^{-8}$. They will also cover regions constrained by Red Giants cooling arguments as well as by EDELWEISS III solar axions searches, thus testing also in this case the potential relevance of ALP environmental effects.

PoS(NuFact2021)090

Acknowledgments

D.K.P. is co-financed by Greece and the European Union (European Social Fund- ESF) through the Operational Programme «Human Resources Development, Education and Lifelong Learning» in the context of the project “Reinforcement of Postdoctoral Researchers - 2nd Cycle” (MIS-5033021), implemented by the State Scholarships Foundation (IKY).

References

[1] **TEXONO** Collaboration, H. M. Chang *et al.*, “Search of axions at the Kuo-Sheng nuclear power station with a high-purity germanium detector,” *Phys. Rev.* **D75** (2007) 052004, `arXiv:hep-ex/0609001 [hep-ex]`.

[2] H. Bechteler *et al.*, “The spectrum of γ radiation emitted in the FRJ-1 (Merlin) reactor core and moderator region,” tech. rep., Inst. fuer Kernphysik, 1984.

[3] D. Aloni, C. Fanelli, Y. Soreq, and M. Williams, “Photoproduction of Axionlike Particles,” *Phys. Rev. Lett.* **123** no. 7, (2019) 071801, .

[4] S. J. Brodsky, E. Mottola, I. J. Muzinich, and M. Soldate, “LASER INDUCED AXION PHOTOPRODUCTION,” *Phys. Rev. Lett.* **56** (1986) 1763. [Erratum: Phys.Rev.Lett. 57, 502 (1986)].

[5] J. B. Dent, B. Dutta, D. Kim, S. Liao, R. Mahapatra, K. Sinha, and A. Thompson, “New Directions for Axion Searches via Scattering at Reactor Neutrino Experiments,” *Phys. Rev. Lett.* **124** no. 21, (2020) 211804.

[6] F. Avignone, C. Baktash, W. Barker, F. Calaprice, R. Dunford, W. Haxton, D. Kahana, R. Kouzes, H. Miley, and D. Moltz, “Search for Axions From the 1115-kev Transition of ^{65}Cu,” *Phys. Rev. D* **37** (1988) 618–630.

[7] D. Aristizabal Sierra, V. De Romeri, L. J. Flores, and D. K. Papoulias, “Axionlike particles searches in reactor experiments,” *JHEP* **03** (2021) 294.

[8] J. Hakenmüller *et al.*, “Neutron-induced background in the CONUS experiment,” *Eur. Phys. J. C* **79** no. 8, (2019) 699.

[9] **MINER** Collaboration, G. Agnolet *et al.*, “Background Studies for the MINER Coherent Neutrino Scattering Reactor Experiment,” *Nucl. Instrum. Meth. A* **853** (2017) 53–60.

[10] J. Billard *et al.*, “Coherent Neutrino Scattering with Low Temperature Bolometers at Chooz Reactor Complex,” *J. Phys. G* **44** no. 10, (2017) 105101.

[11] V. Belov *et al.*, “The νGeN experiment at the Kalinin Nuclear Power Plant,” *JINST* **10** no. 12, (2015) P12011.

[12] H. T.-K. Wong, “Taiwan EXperiment On NeutrinO — History and Prospects,” *The Universe* **3** no. 4, (2015) 22–37.

PoS(NuFact2021)090