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Light-shining-through-wall cavity setups for probing ALPs

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Light feebly-interacting pseudoscalar particles appear in modern particle physics in various ways. Originally, a pseudoscalar particle called an axion was proposed in late 1970s to explain the strong CP problem in quantum chromodynamics [1]. More general axion-like-particles (ALPs) are motivated by the string theory and appear in its low-energy phenomenological description [2]. In addition to the motivation for the particle physics models, axions and ALPs are of a great interest in cosmology because they could make up a significant fraction of the dark matter in the Universe [3–5].

The Lagrangian for interacting ALPs and photons can be written as follows

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2}\,\partial_\mu a\,\partial^\mu a - \frac{1}{2}\,m_a^2 a^2 - \frac{1}{4}\,g_{a\gamma\gamma}\,a\,F_{\mu\nu}\tilde{F}^{\mu\nu}\,, \quad (1)$$

where $F_{\mu\nu}$ is the electromagnetic tensor and $\tilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta}F_{\alpha\beta}$ is its dual, a is the ALP field of mass m_a with dimensionful photon-axion coupling $g_{a\gamma\gamma}$. Generally, m_a and $g_{a\gamma\gamma}$ are treated as independent parameters.

A popular strategy of ALP searches is related to the cosmological (dark matter) and astrophysical probing. These ALPs can be detected by ground- based haloscopes (detection of dark matter ALPs) and helioscopes (ALPs can be produced hypothetically in the Sun) [6] (see, e.g., [7] for a recent review).

Another approach to probing ALPs implies both their production and detection in a laboratory, and usually called Light-Shining-through-Wall (LSW) experiments [8–10]. The LSW setups consist of two cavities separated by a non-transparent wall. ALPs are produced in the first cavity by interaction of electromagnetic field components. Generated ALPs can pass through the wall and convert back to photons in the detection cavity. High intensity of initial electromagnetic field and the resonant amplification for the signal inside the cavities are required because of the extremely small coupling $g_{a\gamma\gamma}$. Two wavelength ranges of EM fields are applicable to LSW: the optical range setup including high intensity lasers and the radio range setup consisting of radio frequency cavities with high quality factors. Both ideas were realised in the experiments, ALPS (optical) [11] and CROWS (radio) [12]. These experiments set the bound $g_{a\gamma\gamma} \simeq 10^{-7}\,\text{GeV}^{-1}$ for a wide range of ALP masses. However, this bound is three orders of magnitude weaker than the CAST helioscope limit $g_{a\gamma\gamma} \lesssim 6\times10^{-11}\,\text{GeV}^{-1}$, [6]. For the moment, the ALPS-II laser experiment [13] is under construction and its projected sensitivity exceeds CAST level.

In addition, the LSW radio experiments aimed at the ALP searches are of a great interest [14]. Recently, several proposals with LSW radio cavities appeared in the literature including superconducting radio frequency (SRF) cavities [15, 16]. In this letter we compare different LSW cavity setups including modification of the CROWS [12]. Specifically, we study four setups:

(i) an electromagnetic pump mode plus static magnetic field in the emitter cavity, static magnetic field in the receiver cavity [10], we call this setup **MF emitter + M*F receiver**;

(ii) two electromagnetic pump modes in the emitter cavity; an electromagnetic pump mode in the receiver cavity [15], we specify this facility as **MM emitter + M*M receiver**;

(iii) two electromagnetic pump modes in the emitter cavity, static magnetic field in receiver cavity [16], we label this proposal as **MM emitter + M*F (RF) receiver**;

(iv) an electromagnetic pump mode plus static magnetic field in the emitter cavity, an electromagnetic pump mode in the receiver cavity, we denote this setup as **MF emitter + M*M receiver**.

Another aspect of our analysis is geometry of the setup which can be adjusted in order to achieve higher sensitivity to ALPs parameters. We study transfer of

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Table 1. Comparison of the characteristics for various experimental setups. The geometrical formfactor $|\mathcal{G}|$ and the setup sensitivity $g_{a\gamma\gamma}$ are presented for the best ratio of R/L of coaxial location and the mass of ALPs $m_a \lesssim \omega_a/2$

Type of the setup	$B_0^{\mathrm{em},(1)}$	$B_0^{\mathrm{em},(2)}$	B_0^{rec}	Q_{rec}	P_{em}	$\|\mathcal{G}\|$	$g_{a\gamma\gamma}$
MF em. + M*F rec.	0.01 T	3 T	3 T	10^5	100 kW	10^{-2}	$3\times10^{-11}\,\mathrm{GeV}^{-1}$
MM em. + M*M rec.	0.1 T	0.1 T	0.1 T	10^{10}	0.1 kW	10^{-3}	$5\times10^{-11}\,\mathrm{GeV}^{-1}$
MM em. + M*F rec.	0.1 T	0.1 T	3 T	10^5	0.1 kW	10^{-3}	$3\times10^{-10}\,\mathrm{GeV}^{-1}$
MF em. + M*M rec.	0.01 T	3 T	0.1 T	10^{10}	100 kW	10^{-3}	$9\times10^{-11}\,\mathrm{GeV}^{-1}$

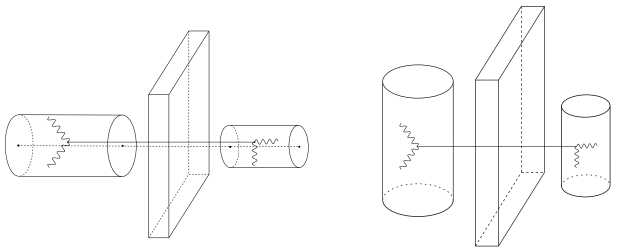

Fig. 1. Two specific types of the experimental configuration consisting of two cylindrical cavities with (left panel) coaxial or (right panel) parallel orientation and screened by axion-penetrable wall. Wavy and solid lines represent electromagnetic field (cavity mode or magnetic field) and ALPs respectively

ALPs from the emitter to the receiver for all aforementioned designs (i-iv) and discuss their optimal configuration, either coaxial or parallel (see, e.g., Fig. 1 for detail). In addition, we investigate $g_{a\gamma\gamma}$ sensitivity dependence on the radius-to-length ratio of production cylindrical cavity.

We summarize our results by presenting important parameters for each setup in Table 1. We concluded that the MF emitter + M*F receiver and the MM emitter + + M*M receiver setups can achieve the similar top sensitivity $g_{a\gamma\gamma} \lesssim (3-5)\times10^{-11}\,\mathrm{GeV}^{-1}$ at $m_a \lesssim \omega_a/2$. In particular, it turns out that the larger electromagnetic field combination and the geometrical formfactor of RF cavities compensate its smaller quality factor. Moreover, we find that the best relative location of the cavities is coaxial with the ratio of $R/L \simeq 1.6$.

The MF emitter + M*F receiver setup is a modification of the CROWS experiment [12] that implies larger volume of the cavities $V_{\mathrm{em}} \simeq V_{\mathrm{rec}} \simeq 1\,\mathrm{m}^3$, lower temperature, and narrower bandwidth of the signal, $\Delta\nu \simeq 1/t$. However, there is a disadvantage of this setup that implies the relatively large emitter power $P_{\mathrm{em}} \sim 100\,\mathrm{kW}$.

The advantage of the MM emitter + M*M receiver setup is that its emitter power is 4 orders of magnitude smaller than the previous one. However, in this case the main technical challenges would be related to the signal mode filtering from the pump mode and fine tuning of cavity sizes.

Given the benchmark parameters, the last two setups, MM emitter + M*F receiver and MF emitter + + M*M receiver, has the weakest sensitivity, see Table 1. Moreover, the typical bounds $g_{a\gamma\gamma} \lesssim \mathcal{O}(10^{-10})\,\mathrm{GeV}^{-1}$ would be ruled out by the CAST. Also, there is a disadvantage of these proposals. In particular, the condition $\omega_1 + \omega_2 = \omega_s$ implies the specific type of the emitter modes, the latter is linked to the sizes of the cavity. Moreover, the modification of the pump modes would require the changing of the receiver geometry. The disadvantages of the MF emitter + M*M receiver include also technical difficulties of the first two setups.

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