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BSM PHYSICS

# The Search for the Axion-Like Particles with Two Radio-Frequency Cavities

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**Abstract**—We discuss probing of the massive axion-like particles (ALPs) by two radio-frequency (RF) cylindrical cavities. We optimize the design of these cavities to perform the effective strategy for the ALPs searches. In particular, we study the radiation pattern and energy density distribution of the ALP field produced in the cavity by two electromagnetic modes. We also discuss the sensitivity of the proposed experimental setup to examine ALPs.

*Keywords*: BSM physics, axion-like particles, LSW experiments

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## 1. INTRODUCTION

Axion-like particles (ALPs) which interact with the gauge bosons of the Stanfard Model arise naturally in several well-motivated New Physics scenarios [1]. Moreover, astrophysics and cosmology observations imply that ALPs are viable candidates for dark matter particles [2–4]. We note that ALPs can be also probed in pure laboratory experiments. Well-known type of such experiments is so-called light-shining-through-wall (LSW) experiments, which consist of two cavities, respecting to the production and detection of ALPs divided by an opaque for electromagnetic field wall. We study an experimental setup of LSW type, in which the production cavity is a superconducting radio-frequency (SRF) cavity of cylindrical geometry filled by two electromagnetic modes, and the detection cavity is an another cylindrical cavity filled with strong magnetic field.

## 2. ALP ELECTRODYNAMICS

The ALP field is described by the massive real pseudo-scalar field $a(\vec{x},t)$ interacting with an electromagnetic field $A_\mu$,

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

where $g_{a\gamma\gamma}$ is the photon-ALP coupling constant, $m_a$ is ALP mass, $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ and $\tilde{F}^{\mu\nu} = \frac{1}{2}\varepsilon^{\mu\nu\alpha\beta}F_{\alpha\beta}$ read electromagnetic field tensor and its dual tensor.

The Lagrangian (1) yields the field equations,

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

$$\partial_\mu F^{\mu\nu} = g_{a\gamma\gamma}\tilde{F}^{\mu\nu}\partial_\mu a. \qquad (3)$$

The first one describes the production of ALPs by an oscillating electromagnetic filed, and the second one describes the ALPs detection due to the photon regeneration in a given electromagnetic background.

## 3. ALP PRODUCTION

The produced ALP field is described by the solution of Eq. (2), which for two pump modes with frequencies $\omega_{1,2}$ in the production cavity reads

$$a_\pm(\vec{x},t) = -\frac{g_{a\gamma\gamma}}{4\pi}$$

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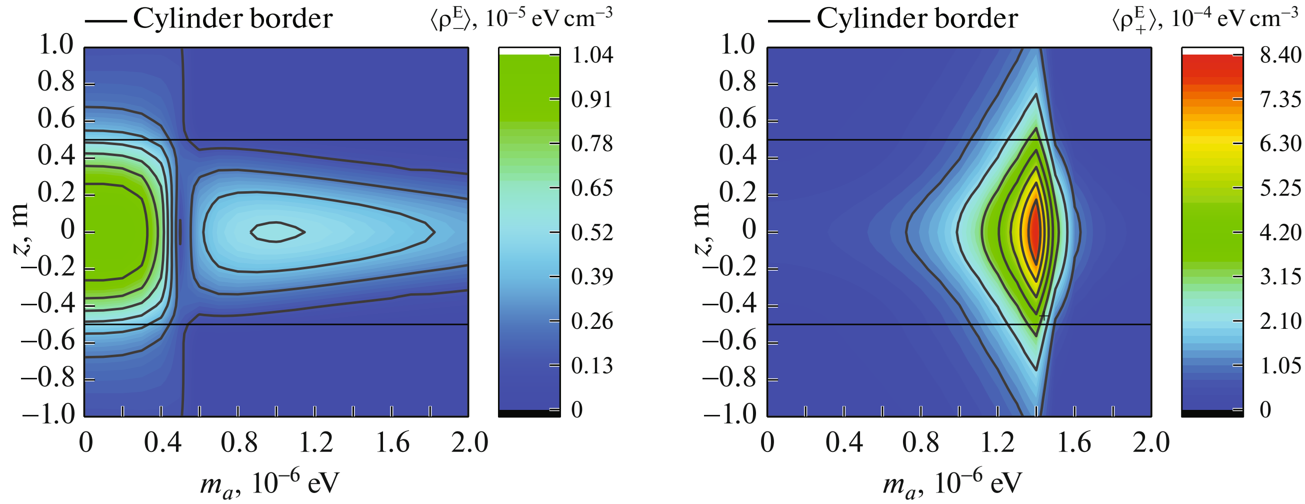


**Fig. 1.** The time-averaged energy density of ALPs frequency components $\omega_-$ (left) and $\omega_+$ (right) for $TM_{010} + TE_{011}$ pump modes.

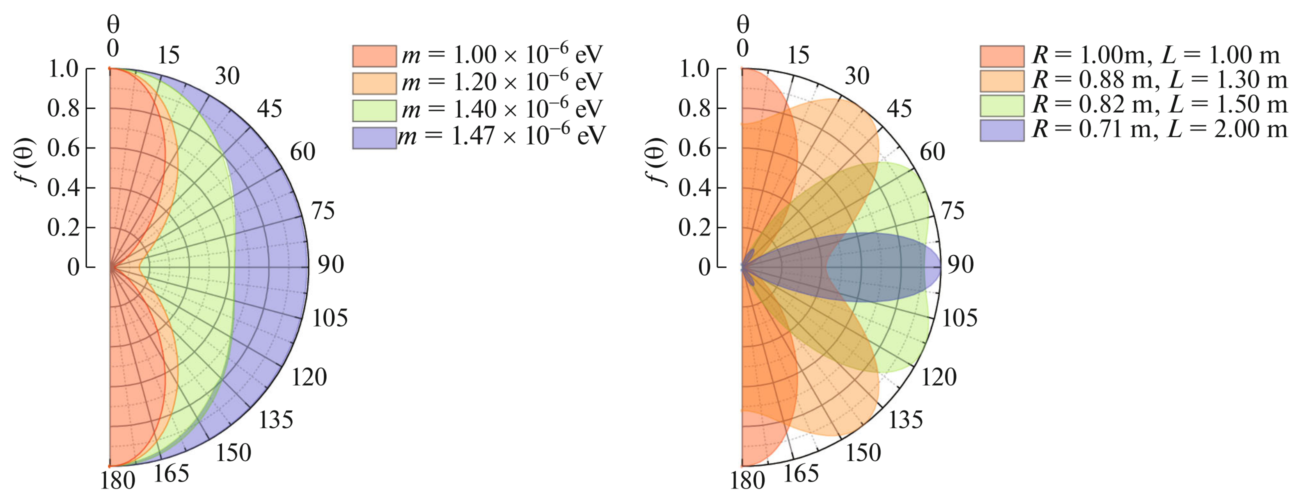


**Fig. 2.** Radiation patterns for ALP emission from a cylindrical cavity filled with $TM_{010} + TE_{011}$ pump modes for various masses of ALPs (left) and cylindrical cavity geometries (right). $R$ and $L$ are the radius and length of the cylindrical cavity.

$$\times \Re e \int\limits_{V_{\rm cav}} d^3x' \, \frac{F_\pm(\vec{x}')}{|\vec{x}-\vec{x}'|} e^{ik_\pm|\vec{x}-\vec{x}'|-i\omega_\pm t}, \qquad (4)$$

where $k_\pm = \sqrt{\omega_\pm^2 - m_a^2}$, $\omega_\pm = |\omega_1 \pm \omega_2|$, $V_{\rm cav}$ is the volume of the production cavity, and $F_\pm(\vec{x})$ are the functions of complex amplitudes of the pump modes. To describe the intensity of ALPs production, it is convenient to use the time-averaged energy density of the ALP field,

$$\langle\rho_\pm^E\rangle_T = \frac{1}{2}\langle\dot{a}_\pm^2\rangle_T + \frac{1}{2}\langle\partial_i a_\pm \partial^i a_\pm\rangle_T + \frac{1}{2} m_a^2 \langle a_\pm^2\rangle_T. \qquad (5)$$

The energy density profiles were numerically computed for different set of modes, cavity geometry, etc., see Fig. 1 and [5] for more details.

## 4. ALP RADIATION PATTERN

In this section we investigate the direction in which ALPs are produced more intensively. The ALP field solution (4) can be expanded in the far distance regime $|\vec{x}| \gg |\vec{x}'|$,

$$a_\pm(\vec{x}, t) = -\frac{g_{a\gamma\gamma}}{4\pi|\vec{x}|} \Re e \, e^{ik_\pm|\vec{x}|-i\omega_\pm t} \int\limits_{V_{cav}} d^3\vec{x}' \, F_\pm(\vec{x}') \times \exp\left[-ik_\pm\left(\vec{x}' \cdot \frac{\vec{x}}{|\vec{x}|}\right)\right] + o\left(\frac{1}{|\vec{x}|}\right). \qquad (6)$$

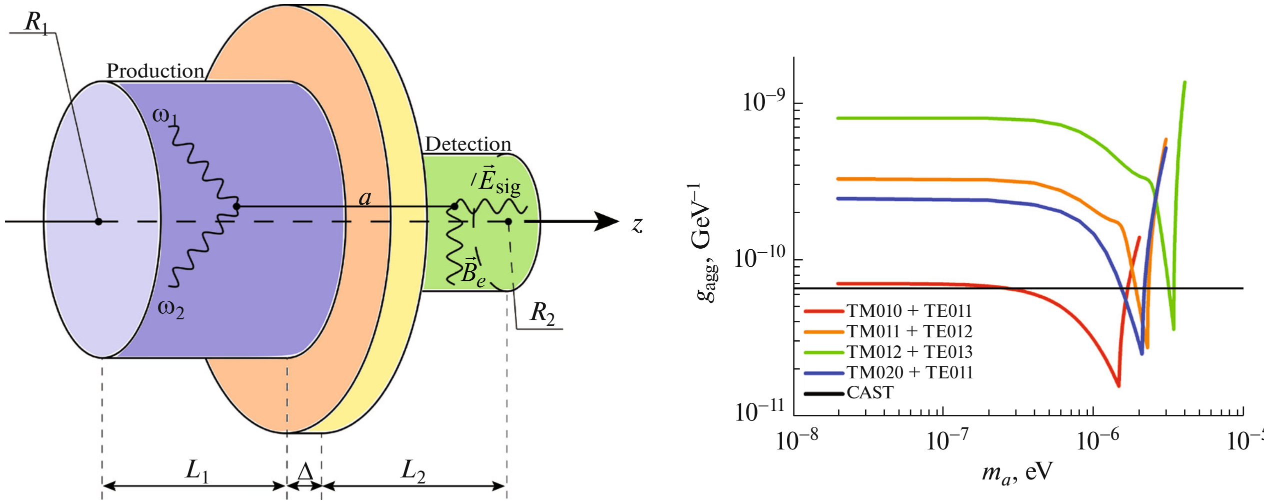


**Fig. 3.** Left: The experiment scheme. Right: Dependence of the coupling constant $g_{a\gamma\gamma}$ on $m_a$ for various pump modes of the production cavity for the $TM_{010}$ mode of the detecting cavity.

Let us define the function $f_\pm(\varphi,\theta)$ to describe the radiation pattern of ALPs emitted from the production cavity,

$$f_\pm(\varphi,\theta) = \lim_{|\vec{x}|\to\infty} \frac{\langle a_\pm^2\rangle_T}{\max\limits_{\varphi,\theta} \langle a_\pm^2\rangle_T}. \qquad (7)$$

The radiation patterns for different ALP masses and cavity geometries are presented at Fig. 2. Note that the radiation pattern is different for thin ($R/L \ll 1$) and thick ($R/L \gg 1$) cylindrical cavities, corresponding to the regime of near-axis emission and the regime of emission in radial direction respectively. Focusing on thin production cavity, we consider ALPs detection with an on-the-axis cavity.

## 5. SENSITIVITY

The amplitude of an electromagnetic mode, generated in an interaction of ALP field with magnetic field $\vec{B}_e$ of the detection cavity, is determined by the solution of Eq. (3). Taking into account the finite quality factor $Q$ of the detecting cavity and fitting the resonance condition with a certain cavity dimensions, one concludes, with the sensitivity for $g_{a\gamma\gamma}$ (for details see [5]),

$$g_{a\gamma\gamma} \simeq 2.52\left(\frac{T\Delta^2\omega_\pm^2}{E_0^4(B_e)^2Q((\kappa_m^{c+})^2+(\kappa_m^{s+})^2)V_{\text{cav}}^2} \times \sqrt{\frac{B}{t}\text{SNR}}\right)^{1/4}. \qquad (8)$$

Here, $T$ is the temperature, $\Delta$ is the length of the screening plate between two cavities, $\kappa_m^{c(s)+}$ are geometrical factors depending on the set of pump modes, $E_0$ and $B$ are the amplitude and bandwidth of pump modes, $t$ is the time of operation, and SNR is signal-to-noise ratio. For experimentally relevant parameters one can obtain the sensitivity up to $g_{a\gamma\gamma} \sim 6 \times 10^{-11}$ GeV$^{-1}$ and even more in the regime of nonrelativistic ALPs (see Fig. 3).

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## CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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