Physics Letters B 777 (2018) 412–419

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Concept of multiple-cell cavity for axion dark matter search

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ARTICLE INFO

Article history:
Received 1 November 2017
Received in revised form 10 December 2017
Accepted 27 December 2017
Available online 3 January 2018
Editor: A. Ringwald

Keywords:
Axion
Dark matter
Microwave cavity
Multiple-cell
Phase-matching

ABSTRACT

In cavity-based axion dark matter search experiments exploring high mass regions, multiple-cavity design is under consideration as a method to increase the detection volume within a given magnet bore. We introduce a new idea, referred to as a multiple-cell cavity, which provides various benefits including a larger detection volume, simpler experimental setup, and easier phase-matching mechanism. We present the characteristics of this concept and demonstrate the experimental feasibility with an example of a double-cell cavity.

1. Introduction

The axion is a hypothetical elementary particle postulated to solve the strong CP problem in quantum chromodynamics of particle physics [1]. With its mass falling in a specific range, the main cosmological interest of the axion at present is its role as a candidate for cold dark matter (CDM) [2], which would account for 27% of the energy of our Universe [3]. If it is CDM, the axion must be an "invisible (very light)" particle of a type of KSVZ [4], DFSZ [5], or their combinations.

A conventional axion dark matter search experiment using microwave resonant cavities adopts the methodological concept proposed by P. Skivie based on the Primakoff effect [6], in which axions are converted into radio-frequency (RF) photons in a strong magnetic field, which are in turn resonated in microwave cavities immersed in the field [7]. The axion-to-photon conversion power is given by

$$P_{a\to\gamma\gamma} = g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} B_0^2 V C \min(Q_L, Q_a), \tag{1}$$

where $g_{a\gamma\gamma}$ is the axion–photon coupling constant, ρ_a is the axion local density, m_a is the axion mass, B_0 is the external magnetic field, V is the cavity volume, and Q_L and Q_a are the quality factors of the loaded cavity and of the axion, respectively [8]. The mode-dependent form factor C is defined as

$$C = \frac{\left|\int_V \mathbf{E_c}\cdot\mathbf{B_0} d^3x\right|^2}{\int_V \epsilon(x)|\mathbf{E_c}|^2 d^3x \int_V |\mathbf{B_0}|^2 d^3x}, \tag{2}$$

where $\mathbf{B_0}$ is the external magnetic field, $\mathbf{E_c}$ is the electric field of the cavity resonant mode under consideration, and $\epsilon(x)$ is the dielectric constant inside the cavity volume. For cylindrical cavities in a solenoidal magnetic field, the TM_{010} mode is commonly considered because it gives the largest form factor. Since the mass of the axion is a priori unknown, a cavity must be tunable to search for a signal over the frequency range determined by the cavity design. It is important to scan a large frequency range as fast as possible with a given experimental sensitivity. A relevant quantity to this is the scan rate whose maximum value is obtained as

$$\frac{df}{dt} = \left(\frac{1}{\mathrm{SNR}}\right)^2 \left(\frac{P_{a\to\gamma\gamma}}{k_B T_{\mathrm{sys}}}\right)^2 \frac{Q_a}{Q_L}, \tag{3}$$

where SNR is the signal-to-noise ratio, k_B is the Boltzmann constant, and T_{sys} is the total noise temperature of the system.

Exploring higher frequency regions in axion search experiments using microwave cavity detectors requires a smaller size of cavity because the TM_{010} resonant frequency is inversely proportional to the cavity radius. An intuitive way to make effective use of a

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https://doi.org/10.1016/j.physletb.2017.12.066
0370-2693/

Fig. 1. Various designs of multiple-detector system: (a) multiple-cavity; (b) multiple-cell cavity; and (c) multiple-cell cavity with a hollow gap in the middle. The dashed line represents the boundary of the magnet bore.

Table 1
Comparison of experimental quantities among various designs of multiple-detector system. V is the total detection volume, Q is the unloaded quality factor at room temperature, and the conversion power and scan rate are values relative to the quadruple-cavity detector. The externally applied magnetic field is assumed to be homogeneous within the magnet bore.

	quad-cavity	quad-cell	sext-cell
V [L]	0.62	1.08	1.02
$f_{\mathrm{TM}_{010}}$ [GHz]	7.30	5.89	7.60
Q	19,150	19,100	16,910
C	0.69	0.65	0.63
$P_{a\to\gamma\gamma}$	1.00	1.65	1.32
df/dt	1.00	2.72	1.98

given magnet volume, and thereby to increase the experimental sensitivity, is to bundle an array of identical cavities together and combine their individual outputs ensuring phase matching of the coherent axion signal [9]. This conventional approach has been experimentally attempted using a quadruple-cavity system [10] but its methodological advantage was not well addressed, and thereby led to a further in-depth study [11].

The multiple-cavity design, however, is still inefficient in volume usage for a given magnet, mainly due to unused volume and cavity wall thickness, as can be seen in Fig. 1(a). One alternative design is a single cylindrical cavity, fitting into the magnet bore, split by metal partitions placed at equidistant intervals to make multiple identical cells, as shown in Fig. 1(b). This concept, initially discussed in Ref. [12], provides a more effective way to increase the detection volume while relying on the same frequency tuning mechanism as that of multiple-cavity systems. The resonant frequency increases with the cell multiplicity. Furthermore, an innovative idea of introducing a narrow hollow gap at the center of the cavity, as seen in Fig. 1(c), provides critical advantages. In this design, all cells are spatially connected among others, which allows a single RF coupler to extract the signal out of the entire cavity volume. This simplifies the readout chain by not only reducing the number of RF antennae but also eliminating the necessity of a power combiner, both of which could be bottlenecks for multiple-cavity systems especially when the cavity multiplicity is large. We refer to this cavity concept as a pizza cylinder cavity.

Using the COMSOL Multiphysics® software [13], this multiple-cell design is compared with the conventional multiple-cavity design in terms of various experimental quantities. Assuming a magnet bore diameter of 100 mm, a cavity height of 200 mm, and a wall thickness of 5 mm, various quantities for a quadruple-cavity system and a quadruple-cell cavity are summarized in Table 1. For a more reasonable comparison, a sextuple-cell cavity whose resonant frequency is similar to that of the quadruple-cavity system is also considered. It is remarkable that, mainly due to the volume increase, the conversion power and scan rate are significantly improved.

2. Analytical EM solution for multiple-cell cavity

2.1. Field solution for perfect electric conductor

With a static external magnetic field $\mathbf{B_0} = B_0\hat{z}$, the axion field a modifies Maxwell equations as in [14]

$$\begin{aligned}
\nabla \cdot \mathbf{E} &= -g\nabla a \cdot \mathbf{B} \approx 0 \\
\nabla \times \mathbf{E} &= -\partial \mathbf{B}/\partial t \\
\nabla \cdot \mathbf{B} &= 0 \\
\nabla \times \mathbf{B} &= \partial \mathbf{E}/\partial t + g(\partial a/\partial t \mathbf{B_0} + \nabla a \times \mathbf{E}) \\
&\approx \partial \mathbf{E}/\partial t + g\partial a/\partial t \mathbf{B_0},
\end{aligned} \tag{4}$$

where $g \equiv g_{a\gamma\gamma}$ and $\nabla a \approx 0$ are attributed to the large de Broglie wavelength of the axion field [11]. The Maxwell–Ampere equation, Eq. (4), is expressed in terms of the vector potential $\mathbf{A}$ with a choice of the Coulomb gauge, $\nabla \cdot \mathbf{A} = 0$, of

$$\nabla \times \nabla \times \mathbf{A} + \partial^2 \mathbf{A}/\partial t^2 = g\partial a/\partial t \mathbf{B_0}. \tag{5}$$

For a cylindrical cavity system, since the EM fields of the TM mode under our consideration form a symmetry in the z direction, the radial and azimuthal components of the vector potential are independent from the vertical component, which leads to:

$$A_r = 0 \text{ and } A_\phi = 0. \tag{6}$$

With the oscillating axion field $a = a_0 e^{-i\omega t}$, Eq. (5) gives

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial A_z}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 A_z}{\partial \phi^2} + \frac{\partial^2 A_z}{\partial z^2} + \omega^2 A_z = -i\omega g B_0 a. \tag{7}$$

Using an ansatz $A_z = R(r)\Phi(\phi) + \Omega(\omega)$, we obtain the general solutions to Eq. (7) as

$$\begin{aligned}
\Omega(\omega) &= -\frac{igB_0 a}{\omega} \\
\Phi(\phi) &= \{e^{\pm im\phi}\} \\
R(r) &= \{J_m(r\omega), Y_m(r\omega)\},
\end{aligned} \tag{8}$$

where $J_m(Y_m)$ is the Bessel function of the first (second) kind for integer or positive m. The curly brackets in Eq. (8) represent linear combinations of the elements inside the brackets. By requiring $A_z(\phi) = A_z(-\phi)$ and $R(0) = $ finite, we obtain the solution for the vector potential,

$$A_z(r,\phi) = A_0 J_m(r\omega)\cos m\phi - \frac{igB_0 a}{\omega}, \tag{9}$$

from which the EM field solutions are obtained:

$$\begin{aligned}
E_z(r,\phi) &= i\omega A_0 J_m(r\omega)\cos m\phi + gB_0 a \\
B_r(r,\phi) &= -\frac{A_0}{r} J_m(r\omega) m \sin m\phi \\
B_\phi(r,\phi) &= -\frac{A_0\omega}{2}(J_{m-1}(r\omega) - J_{m+1}(r\omega))\cos m\phi.
\end{aligned} \tag{10}$$

If we define the enhancement factor $Q_J \equiv |\frac{i\omega A_0}{gB_0 a}|$, the source term $gB_0 a$ can be ignored on resonance since $Q_J \gg 1$. Then the boundary conditions for a perfect electric conducting (PEC) cell as shown in Fig. 2(a), $E_z(r = R_c, \phi) = 0$ and $E_z(r, |\phi| = \theta/2) = 0$, yield

$$\omega = \frac{\chi_{mn}}{R} \text{ and } m = \frac{\pi}{\theta}, \tag{11}$$

where χ_{mn} is the n-th root of the Bessel function of order m. The EM field distributions for the lowest TM mode of a PEC cell with $\theta = \pi/4$ are shown in Fig. 2(b).