Searching for high-frequency axion in quantum electromagnetodynamics through interface haloscopes

Tong Li[1], Chang-Jie Dai[1], and Rui-Jia Zhang[1]

[1]School of Physics ,Nankai University , Tianjin 300071, China

/// arXiv : 2304.12525

Introduction

Axion was originally proposed to solve the Strong CP problem in QCD [1-2], and can play as cold dark matter candidate.

The Witten effect [3] implies the existence of close relationship between axion and magnetic monopole.

A sound quantization in the presence of magnetic monopoles, called QEMD [4-6] which leads to new axion-modified Maxwell equations.

We proposed a new interface haloscopes which place an interface between two electromagnetic media with different properties and are desirable to search for high-mass axions $m_a \gtrsim \mathcal{O}(10)\ \mu eV$.

QEMD

I. THE MODIFIED MAXWELL EQUATIONS OF AXION IN QEMD

Under QEMD, we provide expressions for the axion-induced electromagnetic fields and the propagating waves in different interface setups. We also apply the Poynting's theorem to calculate the energy flux densities and obtain the sensitivity to new axion-photon couplings for high-mass axions.

The QEMD introduces two four-potentials A^μ and B^μ to describe photon. The corresponding U(1) gauge group of QEMD is replaced by $U(1)_E \times U(1)_M$ whose conserved charges are electric and magnetic charges.

Coupling coefficients can be calculated as

$$g_{aAA} = \frac{Ee^2}{4\pi^2 v_{PQ}},\ g_{aBB} = \frac{Mg_0{}^2}{4\pi^2 v_{PQ}},\ g_{aAB} = \frac{Deg_0}{4\pi^2 v_{PQ}}$$

And from the Lagrangian of QEMD ,one can obtain the modified Maxwell equations

$$\partial_\mu F^{\mu\nu} - g_{aAA}\partial_\mu a\tilde{F}^{\mu\nu} + g_{aAB}\partial_\mu a F^{\mu\nu} = j_e^\nu$$
$$\partial_\mu \tilde{F}^{\mu\nu} + g_{aBB}\partial_\mu a F^{\mu\nu} - g_{aAB}\partial_\mu a\tilde{F}^{\mu\nu} = j_m^\nu$$

And the macroscopic form of QEMD Maxwell equations

$$\vec{\nabla}\times\vec{H} - \frac{\partial\vec{D}}{\partial t} = \vec{j}_{e,f} + g_{aAA}(\vec{E}\times\vec{\nabla}a - \frac{\partial a}{\partial t}\vec{B}) + g_{aAB}(\vec{B}\times\vec{\nabla}a + \frac{\partial a}{\partial t}\vec{E}),$$
$$\vec{\nabla}\times\vec{E} + \frac{\partial\vec{B}}{\partial t} = -g_{aBB}(\vec{B}\times\vec{\nabla}a + \frac{\partial a}{\partial t}\vec{E}) - g_{aAB}(\vec{E}\times\vec{\nabla}a - \frac{\partial a}{\partial t}\vec{B}),$$
$$\vec{\nabla}\cdot\vec{B} = -g_{aBB}\vec{E}\cdot\vec{\nabla}a + g_{aAB}\vec{B}\cdot\vec{\nabla}a,$$
$$\vec{\nabla}\cdot\vec{D} = \rho_{e,f} + g_{aAA}\vec{B}\cdot\vec{\nabla}a - g_{aAB}\vec{E}\cdot\vec{\nabla}a.$$

Finally, linear form of Maxwell equations

$$\vec{k}\times\hat{\vec{H}} + \omega\hat{\vec{D}} + i\hat{\vec{j}}_{e,f} = g_{aAA}(\vec{E}_0\times\vec{k}\hat{a} + \omega\hat{a}\vec{B}_0) + g_{aAB}(\vec{B}_0\times\vec{k}\hat{a} - \omega\hat{a}\vec{E}_0),$$
$$\vec{k}\times\hat{\vec{E}} - \omega\hat{\vec{B}} = -g_{aBB}(\vec{B}_0\times\vec{k}\hat{a} - \omega\hat{a}\vec{E}_0) - g_{aAB}(\vec{E}_0\times\vec{k}\hat{a} + \omega\hat{a}\vec{B}_0),$$
$$\vec{k}\cdot\hat{\vec{B}} = -g_{aBB}\vec{k}\cdot\vec{E}_0\hat{a} + g_{aAB}\vec{k}\cdot\vec{B}_0\hat{a},$$
$$\vec{k}\cdot(\omega\hat{\vec{D}} + i\hat{\vec{j}}_{e,f}) = g_{aAA}\omega\vec{k}\cdot\vec{B}_0\hat{a} - g_{aAB}\omega\vec{k}\cdot\vec{E}_0\hat{a},$$

Interface

II. QEMD AXION-INDUCED RADIATION AT AN INTERFACE

We set up a configuration of interface between two regions I and II with a parallel static electromagnetic field B_0 or E_0 , the schematic diagram is shown in figure 1.

The two regions are filled by media with different ε or μ. There are continuity requirements between the two different regions. To satisfy continuity requirements , there is EM propagating waves emit from interface , one can detect the signal of EM waves.

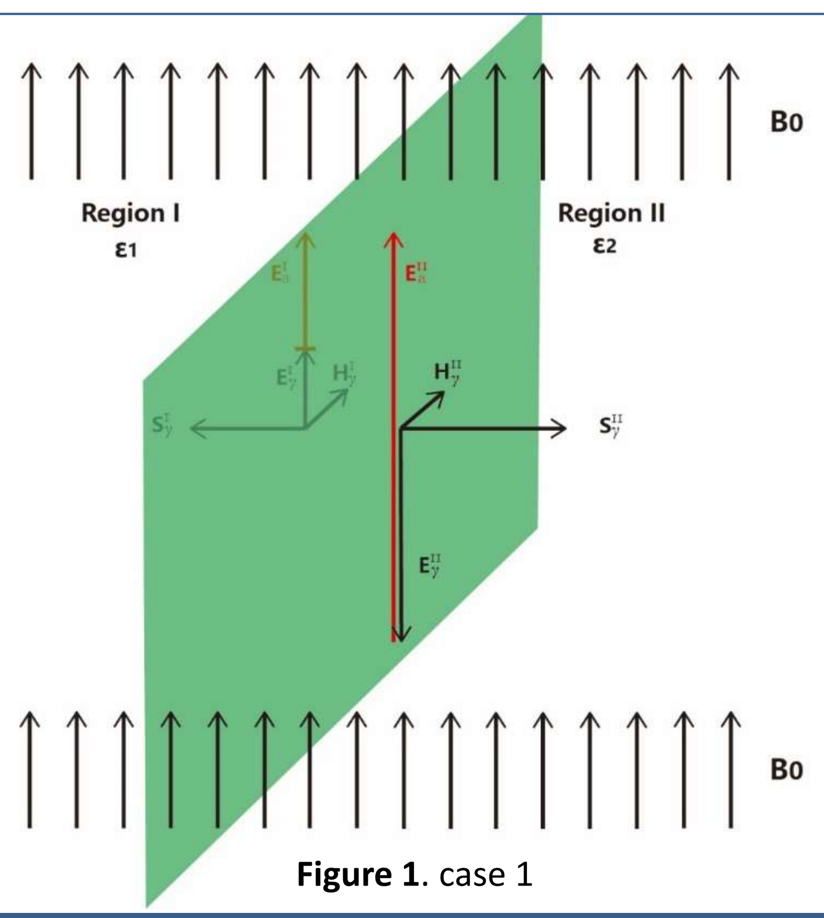

Figure 1. case 1

Solution

III. SOLUTIONS OF EM FIELDS AT INTERFACE

In this paper, we discuss three cases which are designed to detect signal of each coupling coefficients .Following are all the setups of different cases.

Case 1: $\vec{B}_0 \neq 0, \vec{E}_0 = 0, \varepsilon_1 \neq \varepsilon_2$ and $\mu = 1$

Case 2: $\vec{E}_0 \neq 0, \vec{B}_0 = 0, \varepsilon_1 \neq \varepsilon_2$ and $\mu = 1$

Case 3: $\vec{E}_0 \neq 0, \vec{B}_0 = 0, \mu_1 \neq \mu_2$ and $\epsilon = 1$

After calculating Poynting vector of each cases, one can get the signal power P_{signal} .

The results of each cases are as followings

Case1:

$$E_\gamma^I = +\left[E_a^{II} - E_a^I + E_0^{II} - E_0^I\right]\frac{\epsilon_2 n_1}{\epsilon_1 n_2 + \epsilon_2 n_1},$$
$$E_\gamma^{II} = -\left[E_a^{II} - E_a^I + E_0^{II} - E_0^I\right]\frac{\epsilon_1 n_2}{\epsilon_1 n_2 + \epsilon_2 n_1},$$
$$H_\gamma^I = -\left[E_a^{II} - E_a^I + E_0^{II} - E_0^I\right]\frac{\epsilon_1 \epsilon_2}{\epsilon_1 n_2 + \epsilon_2 n_1},$$
$$H_\gamma^{II} = -\left[E_a^{II} - E_a^I + E_0^{II} - E_0^I\right]\frac{\epsilon_1 \epsilon_2}{\epsilon_1 n_2 + \epsilon_2 n_1},$$

Case2:

$$E_\gamma^I = +\left[E_a^{II} - E_a^I + E_0^{II} - E_0^I\right]\frac{\epsilon_2 n_1}{\epsilon_1 n_2 + \epsilon_2 n_1},$$
$$E_\gamma^{II} = -\left[E_a^{II} - E_a^I + E_0^{II} - E_0^I\right]\frac{\epsilon_1 n_2}{\epsilon_1 n_2 + \epsilon_2 n_1},$$
$$H_\gamma^I = -\left[E_a^{II} - E_a^I + E_0^{II} - E_0^I\right]\frac{\epsilon_1 \epsilon_2}{\epsilon_1 n_2 + \epsilon_2 n_1},$$
$$H_\gamma^{II} = -\left[E_a^{II} - E_a^I + E_0^{II} - E_0^I\right]\frac{\epsilon_1 \epsilon_2}{\epsilon_1 n_2 + \epsilon_2 n_1},$$

Case3:

$$H_\gamma^I = +\left[H_a^{II} - H_a^I + \frac{B_0^{II}}{\mu_2} - \frac{B_0^I}{\mu_1}\right]\frac{\mu_2 n_1}{\mu_1 n_2 + \mu_2 n_1},$$
$$H_\gamma^{II} = -\left[H_a^{II} - H_a^I + \frac{B_0^{II}}{\mu_2} - \frac{B_0^I}{\mu_1}\right]\frac{\mu_1 n_2}{\mu_1 n_2 + \mu_2 n_1},$$
$$E_\gamma^I = -\left[H_a^{II} - H_a^I + \frac{B_0^{II}}{\mu_2} - \frac{B_0^I}{\mu_1}\right]\frac{\mu_1 \mu_2}{\mu_1 n_2 + \mu_2 n_1},$$
$$E_\gamma^{II} = -\left[H_a^{II} - H_a^I + \frac{B_0^{II}}{\mu_2} - \frac{B_0^I}{\mu_1}\right]\frac{\mu_1 \mu_2}{\mu_1 n_2 + \mu_2 n_1},$$

Poynting vector

IV. POYNTING VECTOR AT AN INTERFACE

The energy flux density of an EM propagating field is given by the Poynting's theorem as

Case1: $$\overline{S}_\gamma^i = \mp\frac{1}{\sqrt{\epsilon_i}}\frac{(g_{aAA}B_0 a_0)^2}{2}\left(\frac{\epsilon_1 - \epsilon_2}{\epsilon_1\sqrt{\epsilon_2} + \epsilon_2\sqrt{\epsilon_1}}\right)^2$$

Case2: $$\overline{S}_\gamma^i = \mp\frac{1}{\sqrt{\epsilon_i}}\frac{(g_{aAB}E_0 a_0)^2}{2}\left(\frac{\epsilon_1 - \epsilon_2}{\epsilon_1\sqrt{\epsilon_2} + \epsilon_2\sqrt{\epsilon_1}}\right)^2$$

Case3: $$\overline{S}_\gamma^i = \mp\frac{1}{\sqrt{\mu_i}}\frac{(g_{aBB}E_0 a_0)^2}{2}\left(\frac{\mu_1 - \mu_2}{\mu_1\sqrt{\mu_2} + \mu_2\sqrt{\mu_1}}\right)^2$$

Results

V. SENSITIVITY OF INTERFACE HALOSCOPES TO NEW AXION COUPLINGS IN QEMD

Assuming an case with medium II being vacuum. Moreover, the EM wave can be boosted with a series of parallel interfaces. The outgoing wave then becomes a coherent superposition of the transmission and reflection at each interface.

The signal power is given by

$$P_{signal} = A\beta^2\eta\bar{S}_\gamma^{II}$$

Where A is area of disk, β is boost factor , η is power efficiency and $\bar{S}_\gamma^{II}$ is the Poynting vector emit from medium to vacuum.

Plug them into SNR's equation ,one can gain a sensitivity bounds .In figure 2 , we show expected sensitivity bounds of couplings.

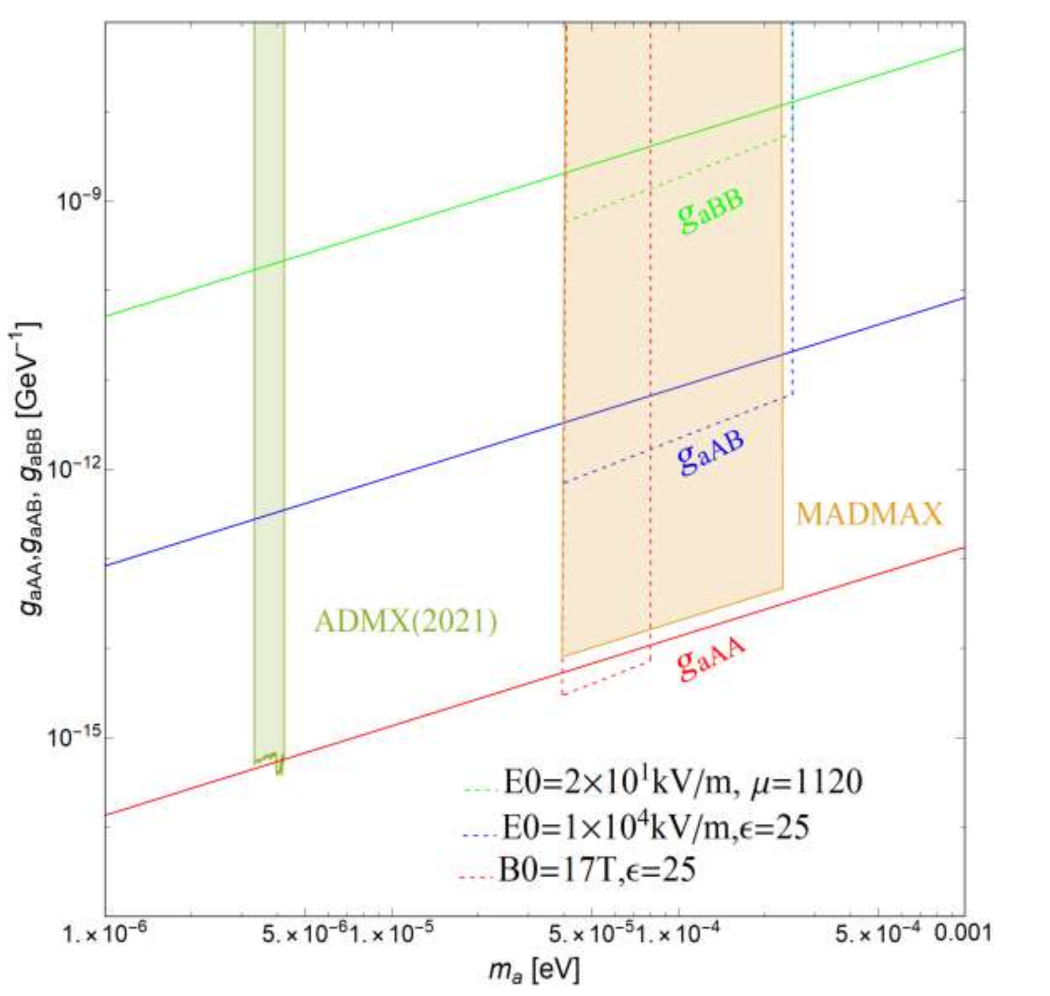

Figure 2. The expected sensitivity bounds.

Conclusions

The configuration of interface between two dielectric regions and a parallel static magnetic (electric) field can measure g_{aAA} (g_{aAB}) coupling.

The configuration of interface between two regions with magnetic material and a parallel static electric field can measure g_{aBB} coupling.

A reasonable setup of interface haloscopes with perfect mirror can probe the theoretical predictions of g_{aAA}, g_{aAB} and g_{aBB} for $\mathcal{O}(100)\ \mu eV \lesssim m_a \lesssim \mathcal{O}(100)\ \mu eV$

References

1. R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. 38, 1440 (1977).
2. R. D. Peccei and H. R. Quinn, Phys. Rev. D 16, 1791 (1977).
3. E. Witten, Phys. Lett. B 86, 283 (1979).
4. J. S. Schwinger, Phys. Rev. 144, 1087 (1966).
5. D. Zwanziger, Phys. Rev. 176, 1489 (1968).
6. D. Zwanziger, Phys. Rev. D 3, 880 (1971).