ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ СО АН СССР

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ANTIFERROMAGNETIC AXIONS DETECTOR

PREPRINT 90-131

НОВОСИБИРСК

Antiferromagnetic Axions Detector

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A B S T R A C T

It is proposed to use an antiferromagnetics with the «easy plane» anisotropy as axion detector. It is shown the response of the detector is proportional to the ratio of the Dzyaloshinsky field to the external magnetic field what allows an increase in the restriction of axion-electron interaction constant.

1. INTRODUCTION

The discovery of long-range forces mediated by massless or very light pseudoscalar particles (arions and axions) would have significant meaning for the formulation of an adequate cosmological model as well as for the study of physics in very small distances. A survey of the stole of experiments in search of some «exotic» long-range interactions is given in [1].

Interaction of axion field a with fermions ψ is discribed by Lagrangian:

$$L_{int} = -qa\bar{\psi}i\gamma^5\psi\,, \qquad (1.1)$$

where q is the axionic charge of fermion.

We will analyze the interaction of field a and a dielectrical magnet. Under relatively low energies, the axion can excite only the spin degrees of freedom of electrons localized on the lattice sites. In this limit, the effective Lagrangian describing interaction of the axionic field with a medium, which follows from (1.1), equals to:

$$L_{ma} = \varkappa\vec{\nabla}a\vec{m}(\vec{r})\,. \qquad (1.2)$$

Here $\varkappa = \mu_a/\mu_B$ is ratio of the axionic magneton of electron, to Bohr magneton, $\mu_a = q/2m_e$, m_e is the electon mass, $\vec{m}(\vec{r})$ is the density of magnetic moment. (Under the derivation of (1.2) the equality $m_e\bar{\psi}i\gamma^5\psi=\partial_\mu\bar{\psi}\gamma^5\gamma^\mu\psi\ +A$ was used. Here A denotes the ignored here contribution of the axionic anomaly leading to direct axion-photonic conversion in the external field [2, 3]. See also [1].)

Such a quasi-magnetic field $\vec{\nabla}a$ can be in a static form and can induce macroscopic magnetization in a paramagnetic sample separated from a ferromagnet by superconductive screen [4]. Experiment [4] according to this scheme, have given a limit for the constant

$$\varkappa<2\cdot10^{-7} \tag{1.3}$$

On the other hand, in the papers [5, 6] it was proposed to generate and detect the dynamical axionic field in ferromagnets. The efficiency of this experiment is provided by the existance of the crossing point of the axion and magnon dispersion curves. In paper [6], a detailed calculation of coefficients of axion-magnon and double magnon-axion-magnon conversion in a ferromagnetic medium was carried out. (At the same time, as [5] it was proposed in [7] to detect galactic axion with wave length from 10 to 100 m using its resonance interaction with a uniform ferromagnetic precession.) Excited in a ferromagnetic detector [5, 6] magnons can be registered through coupled with them electromagnetic oscillations. The quantity of such photons is proportional to $\varkappa^4$.

The independent way to determinate the number of excited magnons is to measure the variation of the macroscopic magnetic field (being proportional to magnetization) by SQUID magnitometer. It is known, however, that for such a measurement it is more effective to use anti-ferromagnets (or weak ferromagnets) with anisotropy of the type of «easy plane» and the strong Dzyaloshinsky field H_D (see, for example [8]). In thise case, the weak ferromagnetic moment taken away by one excited (quasi) Goldstone magnon may be more than the order exciling μ_B (which was used in the work [8]).

In the given paper we study the possibillities of such an anti-ferromagnetic axion detector. We are convinced that the response to the axionic signal measured by SQUID contains the factor of enhancement H_D/H_0, where H_0 is external magnetic field. Additionaly, an experiment of the type [5]. Using generation and detection of axions we may restrict by two orders the limits on the constant $\varkappa$.

2. AXION-MAGNON CONVERSION IN AN ANTI-FERROMAGNETIC MEDIUM

Let $\vec{M}_1$ and $\vec{M}_2$ denotes sub-lattice magnetization of an anti-ferromagnet, $\vec{M}_1=\vec{M}_0+\vec{m}_1$, $\vec{M}_2=-\vec{M}_0+\vec{m}_2$, where $2M_0$ is an equilibrium value of anti-ferromagnetic moment, and $\vec{m}_{1,2}$ are dynamical variables of medium. Let the z-axis be directed along $\vec{M}_0$ and $|\vec{m}_{1,2}|\ll M_0$. Then the transition to canonic variables C_1, C_2 (see, for example [9]), is realized with the substitution. (Here the high nonlinearities are omitted.)

$$M_{1x}+im_{1y}=C_1\sqrt{2\omega_m}\left(1-\frac{g}{4M_0}C_1^*C_1\right),$$

$$m_{2x}-im_{2y}=C_2\sqrt{2\omega_m}\left(1-\frac{g}{4M_0}C_2^*C_2\right),$$

$$\omega_m=gM_0;\qquad g=2\mu_B/\hbar\simeq=2\pi\cdot2.8,$$

$$m_{1z}=-gC_1^*C_1;\qquad m_{2z}=gC_2^*C_2. \tag{2.1}$$

(The classic analog of the transformation of Holstein—Primakoff.) Density of energy of isotropic exchange interaction has the form:

$$\mathcal{H}_{ex}=\alpha\vec{M}_1\vec{M}_2+\beta\partial_i\vec{m}_1\,\partial_i\vec{m}_2. \tag{2.2}$$

For the wave length of interest to us, the contribution of nonhomogeneous exchange can be neglected so that

$$\mathcal{H}_{ex}\simeq\alpha\vec{M}_1\vec{M}_2.$$

We consider here crystals with «easy plane» local anisotropy. Density of energy for such anisotropy, according to our choice of coordinate axes, is equal to:

$$\mathcal{H}_a=\frac{\Omega_a}{\omega_m}(m_{1x}^2+m_{2x}^2), \tag{2.3}$$

where Ω_a is the corresponding frequency. Finally, the Hamiltonian density of Dzyaloshinsky interaction has the form:

$$\mathcal{H}_D=\frac{H_D}{M_0}(M_{1z}M_{2y}-M_{2z}M_{1y}). \tag{2.4}$$

If the substitution (2.1) is fulfilled in a total Hamiltonian

$\mathcal{H}=\mathcal{H}_{ex}+\mathcal{H}_a+\mathcal{H}_D+\mathcal{H}_0$, then we find that h_D contains linear in $C_{1,2}$ terms.

So, the configuration $C_1=C_2=0$ is not a vacuum. The transition to variables describing the oscillation of systems near real equilibrium is realized, by the displacement:

$$C_1\to C_1+i\beta\,; \qquad C_2\to C_2-i\beta\,,$$

$$\beta=-\frac{1}{2}\sqrt{\frac{\omega_m}{2}}\,\frac{H_D+H_0}{\alpha\omega_m}. \tag{2.5}$$

It corresponds to noncollinearity of sublattices in the ground state and the appearance of a weak ferromagnetic moment along the y-axis. Cubic terms of Hamiltonian after displacement (2.5) give a contribution to quadratic terms, which we give in final form:

$$\mathcal{H}=\alpha\omega_m(C_1^*C_1+C_2^*C_2+C_1C_2+C_1^*C_2^*)+$$
$$+\Omega_a\Big(C_1^*C_1+C_2^*C_2+\frac{1}{2}(C_1^2+C_2^2+\text{c.c.})\Big)+$$
$$+\alpha\beta^2g^2\Big\{4(C_1^*C_1+C_2^*C_2)+(C_1C_2+\text{c.c.})-$$
$$-\frac{1}{4}(C_1^2+C_2^2+\text{c.c.})-\frac{5}{2}(C_2^*C_1+\text{c.c.})\Big\}-$$
$$-4\alpha g^2\beta\tilde\beta\,((C_1^*C_1+C_2^*C_2)+(C_1C_2+\text{c.c.})-(C_1^*C_2+\text{c.c.}))\,. \tag{2.6}$$

Here «c.c.» represent complex conjugated parts

$$\tilde\beta=-\frac{1}{2}\sqrt{\frac{\omega_m}{2}}\,\frac{H_0}{\alpha\omega_m}. \tag{2.7}$$

Diagonalization of Hamiltonian density (2.6) is realized by canonic Bogolubov transformations. Under our conditions the lowest frequency mode corresponds to the amplitude d_1, for it:

$$d_1=ub+vb^*\,; \qquad \mathcal{H}=\omega_0 b^*b\,,$$

$$\omega_0=\sqrt{\Omega_0(\Omega_0+\Omega_D)}\,;$$

$$\Omega_0=gH_0\,; \qquad \Omega=gh_D\,; \tag{2.9}$$

$$u\approx\frac{1}{2\xi^{1/4}}(1+\sqrt{\xi})\,; \qquad v\approx-\frac{1}{2\xi^{1/4}}(1-\sqrt{\xi})\,,$$

were

$$\xi\approx\frac{2g^2\beta\tilde\beta}{\omega_m}=\frac{H_0(H_0+H_D)}{4\alpha^2M_0^2}\ll 1\,. \tag{2.10}$$

We have used the inequalities $\alpha\omega_m\gg\Omega_a$, $\alpha\omega_m\gg\Omega_D\gg\Omega_0$ realized when the external field is not too large (for example in $FeBO_3$: $H_D\simeq 100$ kGs).

The expression for the Hamiltonian of interaction of the axionic field with the field b follows from (2.1) and for the case of axionic waves propagating along to z-axis has the form:

$$V=i\sqrt{2}\,g\beta\varkappa\partial_z a(u-v)(b-b^*)\approx i\sqrt{2}\,g\beta\varkappa\xi^{-1/4}\partial_z a(b-b^*)\,. \tag{2.11}$$

It follows from (2.11) that monochromatic axionic wave with frequency ω_0 and amplitude a_0 excites the spin wave with the amplitude

$$b_0=i\sqrt{2}\,g\beta\varkappa\frac{\omega_0}{\gamma}\,\xi^{-1/4}a_0\,, \tag{2.12}$$

where γ is the relaxation frequecy of the spin wave. The corresponding change in static ferromagnetic moment in terms of the Hamiltonian C_1, C_2 has the form:

$$\Delta M_y=-\frac{\beta}{4M_0}\,g\sqrt{\frac{\omega_m}{2}}\,(4(C_1^*C_1+C_2^*C_2)-(C_1^2+C_2^2+\text{c.c.}))\,. \tag{2.13}$$

Considering excitation of the lowest mode (2.12) only taking into account only resonance terms, we arrive at:

$$\Delta M_y\approx-\frac{\beta}{M_0}\,g\sqrt{\frac{\omega_m}{2}}\,(u^2+v^2-uv)\,b_0^*b_0=$$
$$=\frac{3}{2}\sqrt{\frac{\omega_m}{2}}\,\frac{\beta^3}{\xi M_0}\,g^3\varkappa^2a_0\left(\frac{\omega_0}{\gamma}\right)^2\approx\frac{3}{16}\,\varkappa^2(ga_0)^2\left(\frac{\omega_0}{\gamma}\right)^2\frac{H_D}{H_0}\,\frac{\Omega_D}{\alpha\omega_m}\,M_0\,. \tag{2.14}$$

Decreasing the external field we can obtain a great value of the ratio H_D/H_0 and consequently, ΔM_y.

The linear response is enhanced for z component of the magnetization, the amplitude m_z is proportional to $\xi^{-1/2}$.

$$m_z^0\simeq g^2\beta^2\varkappa\frac{\omega_0}{\gamma}\,\xi^{-1/2}a_0\,. \tag{2.15}$$

In the case of infinite medium the oscillations of m_z are pure longitudinal and do not generate. However in a closed resonator of a size comparatible with the wave length the coupling between electromagnetic modes and longitudinal spin waves (2.15) can be of the order of one. It corresponds to the density of generated photon energy:

$$\varepsilon_\gamma \infty \varkappa^2 (a_0 g)^2 \left(\frac{\omega_0}{\gamma}\right)^2 \frac{H_D}{H_0} \left(\frac{\Omega_D}{\alpha\omega_m}\right)^2 M_0^2. \qquad (2.16)$$

3. CONCLUSION

The anti-ferromagnetic detector can be used to search the relict axion having a temperature ~1 K. Another application is in an experiment of the type proposed in the work [5]: the spin wave of large amplitude in the first resonator, generate the axionic wave, freely passes trough a superconductive screen and excites again a spin wave in the second (detecting) resonator. It is evident from (2.15), that for the role of detector the anti-ferromagnetic sample is more suitable, but the generator it is preferable to use a ferromagnet. Indeed the spin waves in an anti-ferromagnet are much more nonlinear that in ferromagnets ones [9], and different instabilities develope under smaller spin wave amplitudes.

The meassurement ΔM_y, with the use of SOUID of the sensitivity 10^{-11} Hs·см^2 will not increase the limit (1.3) on $\varkappa$ noticeably, and may be considered only as an independent experiment with the given accuracy. It is more attractive to use closed resonators and Ridberg photon detector.

We are grateful to I.B. Khriplovich for his active interest and support, P.V. Vorobyev and V.B. Cherepanov for useful advise and many stimulating discussion.

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Антиферромагнитный детектор аксионов

Ответственный за выпуск С.Г.Попов

Работа поступила 16 ноября 1990 г.
Подписано в печать 16.11.1990 г.
Формат бумаги 60×90 1/16 Объем 0,8 печ.л., 0,7 уч.-изд.л.
Тираж 180 экз. Бесплатно. Заказ № 131

Набрано в автоматизированной системе на базе фотонаборного автомата ФА1000 и ЭВМ «Электроника» и отпечатано на ротапринте Института ядерной физики СО АН СССР,
Новосибирск, 630090, пр. академика Лаврентьева, 11.