Ferromaghetic detectors of axions in RF $(S \div X)$ band

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We describe ferromagnetic detectors, for search of arion(axion), where a high-sensitive two-channel SHF receiver is used. Its sensitivity reaches to $10^{-20}\,Wt$*, with time of accumulation* $1 - 10\,s$.

Fourier analysis of signal provides a survey in zone up to $\pm 50\,KHz$ *with spectral resolution* $0.1 - 25\,Hz$.

There was applied a high sensitive SHF receiver based on a special computer method of coherent accumulation of signals. It is possible to use the receiver in other precise experiments: measuring of electron/positron beams polarization in storage rings, investigation of parity violation, investigation of atmosphere with radars etc.

1. Introduction.

The (pseudo) Goldstone bosons arise naturally in many modern theories such as supergravity, superstring theory and variants of general relativity with torsion. In the publications of last years the following (pseudo) Goldstone bosons are discussing: arion, axion, familon, majoron etc (see review [1]).

The experiments on the search of such interactions are interesting from the point of view of fundamental physics (new long-range force) and allow to obtain an information about $10^6 - 10^{19}\,GeV$-physics. It is clear that this energy domain is inaccessible for accelerators.

By the other hand, there are well known indications that a large part of the Universe mass exists in a form of dark matter. The most attractive model of the dark matter is non-relativistic gas of light elementary particles weakly interacting with the "usual" matter [2] - [4].

It means that a non-relativistic electron perceives the axionic condensate as a space-inhomogeneous magnetic field oscillating in time [3]. The effective strength of this field is equal to:

$$B_{eff} = 2\kappa\sqrt{\rho_a}v\sin(m_a t + m_a v x + \theta). \tag{1}$$

Here ρ_a is the density of the condensate, $\kappa = \mu_a/\mu_B$, μ_B is the Bohr magneton and θ is some phase.

The arion-electron interaction looks like the very weak dipole magnetic interaction and may be characterized by the "arionic magneton":

$$\mu_a = k\sqrt{G_F/8\pi} \tag{2}$$

or $\mu_a = 0.7 \cdot 10^{-5} k\mu_B$. Here $k^2 = G_a/G_F$; G_F is Fermi constant.

Let us suppose that v is equal to the "cosmological" velocity of the Earth: $v \approx 10^{-3}$. Then the wavelength corresponding to the space variations of the field B_{eff} can be estimated as

$$\lambda = 0.1 \left(\frac{1eV}{m_a}\right) \ (cm) \tag{3}$$

If $m_a < 1eV$ the length $\lambda \geq 0.1cm$ and for samples of sizes $\sim 1mm$ one can treat the field B_{eff} as a homogeneous one:

$$B_{eff} = b\sin(m_a t + \theta), \quad b = 2\kappa\sqrt{\rho_a}v, \tag{4}$$

where $\kappa = \mu_a/\mu_b$. Such an exotic quasimagnetic field with the amplitude about $10^{-16}Gs$ can be picked up already in the present state of the art. However, methods of its detection depend essentially on the axion mass m_a value being the frequency of the field's B_{eff} oscillations.

For massless arion [1] the equation of motion for the arion field (a) and electron spinor (ψ) are

$$\begin{array}{l} a + \vec{\nabla}(\psi^{+}\vec{\sigma}\psi) = 0, \\ i\frac{\partial}{\partial t}\psi = \left[-\frac{\nabla^2}{2m} - q_{ea}(\vec{\sigma}\cdot\vec{\nabla}a)\right]\psi \end{array} \tag{5}$$

The arion field may be described as the effective magnetic field

$$\vec{B_a} = -2\sqrt{\pi}\vec{\nabla}a \tag{6}$$

The behavior of arion field in the wave zone has been considered in [1]. At large distances:

$$\vec{\nabla}a(\vec{r},t) = -\frac{\vec{r}}{r^2}\left(\vec{n}\cdot\frac{q_{ea}}{8\pi}\int\ddot{\vec{S}}(\vec{r}\prime,t\prime)d^3\vec{r}\prime\right), \tag{7}$$

where $\vec{n} = \vec{r}/r$, $t\prime - |\vec{r} - \vec{r}\prime|$. It is clear that in this case the arion wave the longitudinal polarization: $\vec{\triangle}a \parallel \vec{n}$. Such "ario-dynamics" is the base for constructing arion/axion detectors.

At present time there are used detectors based on coherent conversion $axion(arion) \rightarrow photon$ in transverse magnetic field [5] - [7]. For effective registration of axionic condensate, it is advantageous to use a detector based on magnetized (anti)ferromagnetic. In this case, axion-photon conversion happens not through triangle diagram with charged fermion in loop, but thorough process, analogous Compton-effect on electron bound in atom. It increases α^{-2} times the probability of resonance conversion axion-photon ($\alpha = 1/137$) [8].

So, as for search of cosmological axionic condensate, as for building of a laboratory ferromagnetic detector based on conversion $magnon \rightarrow axion \rightarrow magnon$, we need a high sensitive SHF receiver permitting coherent accumulation of signal.

2. SHF ferromagnetic detector of axions.

If the quasimagnetic field has frequency below 10^6 Hz (what corresponds to $0 < m_a < 10^{-8} eV$) it is natural to use a detector with a ferromagnetic rod as a sensitive body. Its magnetization can be read off by SQUID. Detectors of such a kind have been used already in search of arion and T-odd long-range forces [9] - [11]

In the range $10^8 Hz < m_a < 10^{10} Hz$ ($m_a < 10^{-4} eV$) one can use the resonance axion-magnon conversion in magnetic ordered media [8],[13]. Let us consider a resonator with a working mode TE_{110} and with a small spherical ferrous- or antiferromagnetic sample placed in its center. An external magnetic field is directed in such a way that the averaged magnetization of the sample is perpendicular to the magnetic component of the resonator's eigenmode. The magnetic resonance frequency is fitted to be equal to the eigenfrequency of the resonator. It provides a strong coupling between the magnetic moment oscillations and the electromagnetic ones. If m_a coincides with this frequency the spin waves will be exited resonantly by the axionic wind. Electromagnetic oscillations coupled with such the waves can be detected by a sensitive receiver.

Detailed discussion of the axion-magnon conversion and the corresponding computations can be found in papers [8], [12]. Here we present the result only. If P is a limiting value of intensity which our receiver can detect, M is the sample magnetization, Q_f is the quality of the ferromagnetic resonance and H_0 is the external magnetic field, then the smallest detectable quasimagnetic field is equal to:

$$b \approx \left(\frac{P}{m_a^4}\right)^{1/2} \frac{H_0}{M} \frac{1}{kLQ_f} \tag{8}$$

and for $P = 10^{-15} erg/c$, $m_a = 10^{10} Hz$, $H_0 \sim M \approx 10^3 Gs$ and $(kL)^2 = 10^3$ we obtain $b \approx 10^{-15} Gs$. The use of the antiferromagnetic with a large Dzyaloshinsky field (e.g. $FeBO_3$) as a sensitive body can give an additional factor $\sim 10^{-3}$ in the right hand side of (8) (see [8]).

2.1 A laboratory ferromagnetic detector

Let us consider a laboratory ferromagnetic detector for search of axions [8]. Its main idea is following. A powerful SHF generator excites the resonance precession of electrons' spins in ferromagnetic, filling a waveguide-resonator. Spin's coherent precession excites an axion wave which spreads along waveguide axis and leaves it. The axion wave penetrates freely through system of electromagnetic screens gets into receiving waveguide where it excites the resonance precession of spin in ferromagnetic. The procession magnetic moment of ferromagnetic produces an electromagnetic wave in the receiving waveguide-resonator; High-sensitive coherent RF receiver registries this electromagnetic wave.

We see, there happens the double conversion in detector:

$$photon \rightarrow magnon \rightarrow axion \rightarrow magnon \rightarrow photon.$$

The work of ferromagnetic detector would be much more effective if we use a high sensitive receiver providing a coherent accumulation of signal.

The usage of the coherent detection scheme with quadrature component registration leads to the square root of N increase in the Signal-to-Noise (SNR) ratio as compared to the non coherent scheme, where N is the number of accumulation cycles.

The general idea of the detector is following: The detector has a two-channel quadrature superheterodyne receiver with a heterodyne, common for the both channels. As a base generator, the heterodynes use a highly stable Rb frequency generator. The signal of ferromagnetic resonance (induced with axion field in the receiving waveguide-resonator) feeds to the first (high sensitive) receiver channel input, is heterodyning, splits into its quadrature components and, after the matched filters, is registrating by couple of ADC's. The "pilot-signal" of generator, through a "directed divider" and attenuator, feeds to the second receiver channel input, and also heterodynes, splits into its quadrature components and is digitizing by second couple of ADC's.

The overall synchronization is provided by the computer controlled generator of synchronization pulses.
As the accumulation is completed, the data are read from the ADCs' buffers into the computer where some sufficient processing takes place (a statistical analysis of data in order to calculate zero levels and other hardware parameters; based on it, distinguishing of pure quadrature components and compensation of their non-orthogonality; reducing to the quadrature basis of the "pilot-signal" and the further Fourier analysis).

Such detector, with operating frequency is $9\,GHz$*, was constructed in BINP. There was obtained following limit for the for electron-axion coupling constant:* $q_{ae} < 10^{-3}\,GeV^{-1}$ *or* $B_{eff}/B_0 < 10^{-12}$ *for distances less* $5\,mm$.

2.2 HALOSCOPE - detector of cosmological axion condensate.

Let us consider a detector of the cosmological axion condensate, HALOSCOPE [3]. It consists of SHF resonator, working in mode TE_{011}. In the center of resonator, in the bunch of magnetic field, there is placed a little spherical sample, made of (anti)ferromagnetic of high ferromagnetic resonance quality. The resonator is placed into constant external magnetic field so that the sample's magnetization is perpendicular to the magnetic component of resonator SHF field.

We select such magnitude of external magnetic field that the frequency of ferromagnetic resonance corresponds the own frequency of resonator at mode TE_{011}.

Let the detector move through the axion condensate so that the vector of effective quasimagnetic field $\vec{b}$ is perpendicular to the external field. If the field oscillation frequency $\vec{b}$ coincides with the the frequency of ferromagnetic resonance then a precession of ferromagnetic magnetization vector will take place. There appears an oscillating component of the sample's magnetic moment; it is well linked with the magnetic field TE_{011} of the resonator's oscillation.

This linkage provides a transmission of power from quasimagnetic wave to resonator's electromagnetic field (and back) which is possible to registry by a high sensitive RF receiver.

There are possible two ways to use the receiver:

1) The signal of ferromagnetic resonance feeds to the high sensitive receiver input, and is slitting into its quadrature components, relatively basis formed by very stable heterodyne. In this case, we do not need the low sensitive support channel for "pilot-signal".

2) A "pilot-signal" from very stable generator is using; it feeds to a support channel input (low sensitive). This way looks more advantageous because:

- We can use SHF-modules of standard SHF receivers like "7-8", "7-11" and other ones which contains SHF-amplifier, heterodyne etc. A low stability of own first heterodyne does not matter because the coherentness is provided by high stable "pilot-signal" which is easy to obtain.

- It is not necessary for the "pilot-signal" to be, simultaneously, very stable and powerful enough.

- The "pilot-signal" may be used for adjusting of ferromagnetic resonance and for calibration of detector (among measurement cycles).

This detector was constructed in BINP for operation in range $2-12\,GHz$. *We scanned range* $8-10\,GHz$ *with sensitivity* $B_{eff} < 10^{-14}\,Gs$. *For this sensitivity level no axionic signal was found. It is a preliminary result; we hope to perform a full scanning* ($2-12\,GHz$) *with better sensitivity.*

To increase sensitivity, we used in this work the method of coherent accumulation and modulation of magnetized field.

3. High-sensitive SHF receiver

We constructed a complex of tho-channel coherent receivers covering scope from $100\,MHz$ to $12\,GHz$ [14].

The receivers are made by classic heterodyne scheme with double frequency transformation. To provide the coherence, a computer processing was used.

For each channel, the signal is heterodyned and split into its inphase and quadrature components, which are digitized by couple of ADC's and, after accumulating cycle, are read by computer.

A special very effective procedure performs a statistical analysis of accumulated sequences and calculate floating zeros (of all tract of measure including ADCs) and parameters of non-orthogonality of the quadrature splitter. After this procedure, there becomes possible to obtain pure quadrature components of signals and to compensate their non-orthogonality.

As the quadrature components are calculated, every couple of quadratures from accumulating signal array is reduced to the quadrature basis of corresponding couple of "pilot signal's" quadratures or, the same, random initial phases of "pilot signal" are subtracted from the phases of accumulating signal.

So a coherent sequence of accumulating signal's quadratures is obtained; and its Fourier analysis and other necessary processing are performing.

Using this method, there was reached the sensitivity $-180\,dB$, while accumulating sequence of length 4096.

Another complex was used in radar for investigation of atmosphere, with work frequency of $150\,MHz$. Its sensitivity is $-190\,dB$ [15].

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