POSSIBILITIES OF DARK MATTER ELEMENTARY PARTICLES REGISTRATION

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The paper considers the modern opportunities for experimental detection of dark matter particles (axions). In accordance with the theoretical predictions, these particles have very small rest mass corresponding to the energy in the range of 0.001... 1.0 meV. It discusses the possibilities of the visible range laser radiation conversion into the emission of axions both in vacuum and in material media as well as the inverse processes using experimental facilities for the Primakoff effect observation ("Light shining through wall"). It is proposed to implement a stimulated photon-axion conversion for pumping while using the pulsed laser sources with a high spectral intensity of radiation. To improve the efficiency of the photon-axion conversion, it is also suggested to use the dielectric media characterized by the presence of unitary polaritons in their spectrum, if their refractive index is close to one. In this case, the synchronism conditions can be fulfilled during an elementary process of axion-photon conversion. Schemes of the possible experiments are presented to observe the processes of conversion of axions into microwave photons at low temperatures in a strong magnetic field.

Keywords: axion, parafoton, resonator, receiver, rest mass, conversion, laser, generation.

According to the modern concepts of high-energy physics [1-4] about scenarios for the evolution of the Universe, after the initial homogenious and isotropic state of the physical vacuum, an irreversible phase transition occurred that resulted in reduction of the vacuum symmetry. The so-called standard model of this phase transition is based on the use of local (gauge) symmetry specified by the group $\mathrm{SU}_2 \times \mathrm{U}(1)$. The conclusion of this theory is the prediction of the scalar field formation in vacuum, specifying the symmetry of low temperature phase and leading to the formation of massive elementary particles. In particular, in the spectrum of elementary particles in a high-energy field, the existence of a "heavy" scalar particle — the Higgs boson [4–7], has been predicted, which is being intensively searched for in recent years using experimental facilities, which generate elementary particles with the energy above 1 TeV. This particle is supposed to be detected as a result of the analysis of the allowed processes of scalar Higgs boson decay into pairs of gamma-quanta, the presence of which may be determined by traditional methods known in elementary-particle physics. Along with a scalar Higgs boson, also called amplitudon, in the theory of phase transition in vacuum there is a massless Nambu – Goldstone boson called phason.

In recent years it has become clear that despite the great success of describing a wide range of the currently known elementary particles, the standard model requires further clarification considering the discovery of symmetry breaking effects of time (T) reversal at small distances. Thereby, the theory predicts that the phason rest mass must be different from zero. Thus, the conclusion is made about existence of the elementary particles with extremely small but finite rest mass [8–11]. Axions can be the examples of such particles [1]. The axion rest mass is expected to correspond to the energy range of 0.001... of 1.0 meV, i.e., it must be considerably less than the rest mass of all known elementary particles. Axions are pseudo-scalar particles, i.e. their wave function changes the sign under inversion and mirror reflections of space.

The current trend in modern physics is also associated with predicting the presence of the dark matter in the Universe (total share is 0.23) and the dark energy (total share is 0.73).

Recently a hypothesis has been put forward based on astrophysical data [12–17] that the axions, which are pseudo-scalar particles with the extremely low rest mass and relativistic law of dispersion, can be contenders for the role of dark matter particles.

“Cold” (slow) axions are nonrelativistic (Newtonian) particles. They can turn into the state of Bose-Einstein condensate in case of having a density high enough to perform it. “Hot” (fast) axions are relativistic particles and move at speeds close to the speed of light. An important property of these particles is their hyperweak interaction with the material media, this property being similar to neutrino’s. According to the estimates based on astrophysical data, the equilibrium concentration of axions in our part of the Galaxy is about 10^{-24} g/cm^3. With this concentration, due to the extremely low rest mass of axions, the Bose-Einstein condensation must occur, even at room temperature.

Some papers discussed the problem of detecting and generating axions in the laboratory [12–17]. The possibilities of realization of photon-axion conversion processes are being analyzed along with the inverse processes that are allowed by the selection rules in the presence of a strong external magnetic field. The two effects are being studied: 1) generation of “hot” axions during the photon conversion of the laser or x-ray radiation into the axions of the same energy; 2) detection of “cold” (Newtonian) axions in their conversion into microwave range photons. Only the first experimental results have recently been obtained in these areas that require optimization of the observation conditions and finding ways to strengthen the effectiveness of the processes being discussed to find a reliable interpretation of the obtained experimental results.

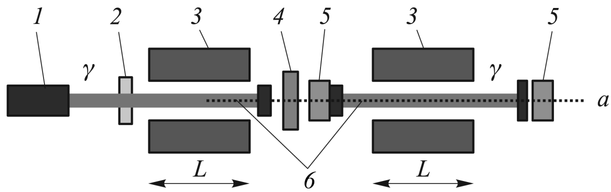


Fig. 1. Basic diagram of the experimental setup to observe the laser radiation photon conversion into pseudo-scalar bosons→(axions) and the inverse process of reconversion →′ using cavities: *1* — laser radiation source; *2* — semitransparent cavity mirror; *3* — solenoids; *4* — non-transparent wall; *5* — secondary radiation detectors; *6* — Fabri – Perot interferometers

The new experimental setups of axions generation and detection are presented in this paper and opportunities for their laboratory testing are analyzed.

Generation and detection of "hot" axions in the visible spectrum. In papers [18–21] considering the evolution of stars with masses of 8. . . 12 times the mass of the Sun the conclusion was made about the course of photon-axion conversion processes inside the stars, and estimates of the upper constant of the photon-axion conversion were received. Moreover, in papers [10–12, 15] an assumption was made about the possibility of creating "hot" axion flows with the energy 2. . . 3 eV in a laboratory setting while conducting the experiments like "Light shining through wall" (the so-called Primakoff effect). The basic diagram for generating and detecting axions using the Primakoff effect is shown in Figure 1. At the first stage with the help of modern lasers of visible light that generate light quanta (γ), the process of photon-axion conversion is implemented ($\gamma \leftrightarrow a$). The resulting axions (a) penetrate the wall *4* into the second cavity. The inverse processes ($a \to \gamma'$) of axions conversion into secondary photons (γ') can occur in this cavity, which are registered by detector *5*.

As a result of the secondary photon detection after the reconversion process, the probability of these processes occurrence should be estimated as well as the efficiency of "hot" axions photoproduction in the laboratory.

According to the selection rules, the processes of photon-axion conversion can occur only with the imposition of a constant magnetic field in the area of laser radiation scattering, the induction of this magnetic field being perpendicular to the direction of the exciting radiation beam. It causes the direct processes of photon-axion transformation. In the absence of the external magnetic field, only three-particle conversion processes are allowed, their probability of occurrence being low.

As it has become clear from the experiments made [10–12, 15], the observed signal of the secondary radiation resulting from the reconversion process has turned out to be extremely small, and at this stage of the experiments it is below the threshold of sensitivity of the modern radiation

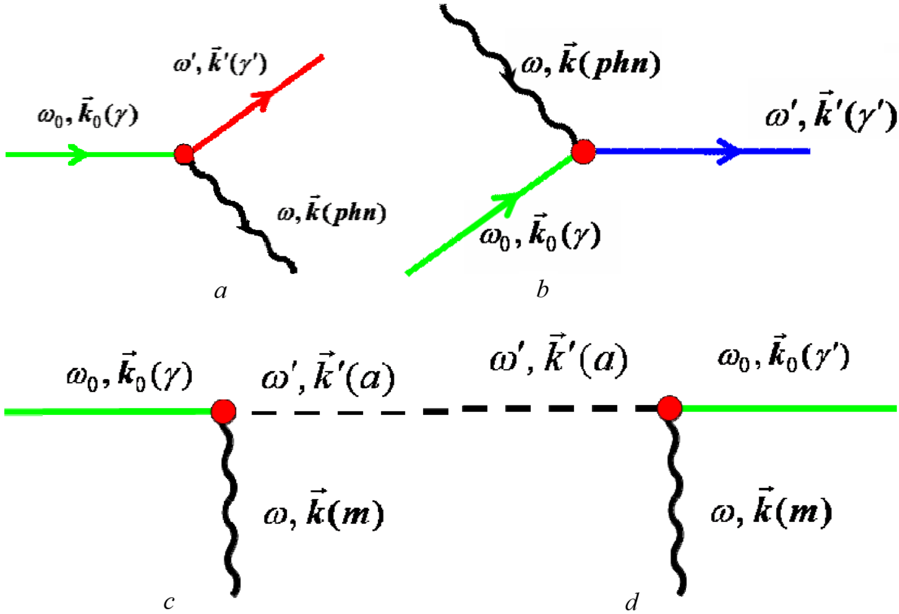


Fig. 2. Diagrams of elementary processes of Stokes CS (*a*) and anti-Stokes CS (*b*); diagrams of photon-axion conversion processes (*c*) and axion-photon reconversion processes (*d*)

detectors. The probability of the conversion-reconversion processes is stipulated by the interaction constant g of the axional and electromagnetic fields in vacuum, the value of g according to the recent estimation being $g \approx 10^{-10}\,\text{GeV}^{-1}$.

Let us consider the processes of light combinational scattering (CS) in crystals [10–12, 15, 21–23] as the analogue of photon-axion conversion processes. The diagrams of elementary processes of Stokes CS and anti-Stokes CS are shown in Fig. 2, *a, b*.

In the first case A light quantum (photon) disintegrates into another photon and a crystal quasiparticle (an optical phonon) during each CS elementary process. The energy of the photon resulting from the inelastic scattering action decreases. In the second case an inelastic “collision” of the photon with the phonon occurs, which results in a photon with higher energy. In elementary processes of Stokes SC and anti-Stokes CS, the laws of conservation of energy and momentum (quasi-momentum) are fulfilled. In particular, for Stokes CS (Fig. 2,*a*) the following equations are used:

$$\begin{aligned} \hbar\omega_0 &= \hbar\omega' + \hbar\omega; \\ \hbar\vec{k}_0 &= \hbar\vec{k}' + \hbar\vec{k}. \end{aligned} \qquad (1)$$

Here $\hbar\omega_0, \hbar\omega', \hbar\omega$ are the energies of exciting radiation photons, scattered radiation and an optical phonon of the crystal; $\hbar\vec{k}_0, \hbar\vec{k}', \hbar\vec{k}$ are the corresponding momentums (quasimomentums). In the case of anti-Stokes

CS (Fig. 2, b) the laws of conservation for an elementary scattering action will take the form of:

$$\hbar\omega_0 + \hbar\omega = \hbar\omega';$$
$$\hbar\vec{k}_0 + \hbar\vec{k} = \hbar\vec{k}'.$$

The Stokes process of exciting radiation photon decay into an axion and a virtual photon of the magnetic field becomes possible in the elementary CS process during the photon-axion conversion in a constant external alternating magnetic field (Fig. 2). In the anti-Stokes process a "collision" of the exciting radiation photon with the photon of the external magnetic field occurs, resulting in generating an axion – the low energy pseudoscalar boson (Fig. 2, *c, d*). If the magnetic field is alternating, the virtual photons relating to the external magnetic field are the real particles and are characterized by the frequencies of the alternating magnetic field.

For the Stokes and anti-Stokes processes of the photon-axion conversion, the laws of conservation will consequently take the form of:

$$\begin{aligned} &\hbar\omega_0 = \hbar\omega' + \hbar\omega; \\ &\hbar\vec{k}_0(\gamma) = \hbar\vec{k}'(b) + \hbar\vec{k}(m); \end{aligned} \tag{2}$$

$$\begin{aligned} &\hbar\omega_0 + \hbar\omega = \hbar\omega'; \\ &\hbar\vec{k}_0(\gamma) + \hbar\vec{k}(m) = \hbar\vec{k}'(b). \end{aligned} \tag{3}$$

If the external magnetic field is constant, the relations (2), (3) become simpler and are transformed into:

$$\begin{aligned} &\hbar\omega_0 = \hbar\omega'; \\ &\hbar\vec{k}_0(\gamma) = \hbar\vec{k}'(b). \end{aligned} \tag{4}$$

The inverse process — the reconversion of axions into photons — is also possible (Fig. 2, d). In this case the Stokes and anti-Stokes processes are possible, for which the following relations are used:

$$\hbar\omega' = \hbar\omega_0 + \hbar\omega;$$
$$\hbar\vec{k}'(b) = \hbar\vec{k}_0(\gamma) + \hbar\vec{k}(m).$$

If the external magnetic field is constant, then:

$$\begin{aligned} &\hbar\omega' = \hbar\omega_0; \\ &\hbar\vec{k}'(b) = \hbar\vec{k}_0(\gamma). \end{aligned} \tag{5}$$

Thus, the processes of photon-axion conversion and reconversion in a magnetic field are similar to the processes of the Stokes CS and anti-Stokes CS in crystals. If in the field of the scattered radiation inside a crystal, active for the CS, there are n_s light quanta of CS per one mode of the electromagnetic field and m_i optical phonons, allowed by the selection rules for CS, per one mode of the phonon field, then the full probability $W^{(s)}_{n_s+1;m_i+1}$ of the Stokes CS in this crystal (the speed of the process, 1/sec) can be written as follows [22]:

$$W^{(s)}_{n_s+1,m_i+1} = (n_s + 1)(m_i + 1)W^{(s)}_i = (n_s + 1)W^{(s)}_{sp}.$$

Here value $W^{(s)}_{sp} = (m_i+1)W^{(s)}_i$ has been introduced that characterizes the probability of a spontaneous CS. With the increase of pumping intensity, one of the optical modes of the crystal, which are active for CS (as a rule, corresponding to the most intensive line of the spontaneous CS), can be characterized by the transition from the spontaneous CS regime to the stimulated (forced) CS–SCS. The relationship between the probabilities, 1/sec, for SCS $W^{(s)}_{st}$ and spontaneous CS $W^{(s)}_{sp}$ is, according to (1), as follows:

$$W^{(s)}_{st} = n_s W^{(s)}_{sp}. \tag{6}$$

With regard to (6) for the intensity $I^{(s)}_{st}$ SCS, we can write down:

$$I^{(s)}_{st} = n_s I^{s}_{sp}, \tag{7}$$

where I^{s}_{sp} is the intensity of the spontaneous Stokes CS process. With the sufficiently high intensity of pumping exceeding the threshold of SCS occurrence, the following relation is true for the SCS intensity:

$$I^{(s)}_{st} = I^{(s)}_{sp}(0)\exp(\alpha I_0 z).$$

Characteristic values of the ratio α in SCS-crystals are around 0,01 cm/MW. On the crystal being one cm long and having the pumping power density of $I_0 \approx 10^8$ W/cm^2, the SCS intensity is equal to:

$$I^{(s)}_{st} = (0.1 - 0.01)I_0.$$

Therefore, at the output of the crystal the SCS intensity increases abnormally and becomes comparable with the intensity of pumping. At the same time the value n_s becomes comparable with the value $n_0 \approx 10^{14}$, where n_0 is the number of light quanta per one mode of the exciting radiation field for ultrashort (10^{-10} s.) intensive ($I = 10^{12}$ W/cm^2) pulses of a solid-state visible laser (0.5 μm).

Let us describe the photon-axion conversion in the physical vacuum. At the first stage we will focus on the spontaneous processes. In accordance with the theory [11–17] we assume the Lagrangian density of the system in question as a sum of the density of the electromagnetic field Lagrangian, the density of the axion field ϕ_a Lagrangian, and a summand allowing for these fields interaction.

The density of the field Lagrangian written with regard to the electromagnetic field interaction with the pseudoscalar boson field is written as follows:

$$\Im = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}(\partial_\mu\phi_a\partial^\mu\phi_a - m_a^2\phi_a^2) - \frac{1}{2}g\phi_a F_{\mu\nu}\tilde{F}^{\mu\nu}. \qquad (8)$$

Here $F_{\mu\nu}$, $F^{\mu\nu}$ are electromagnetic field tensors; $\tilde{F}^{\mu\nu} = (1/2)\,\varepsilon_{\mu\nu\lambda\rho}F^{\lambda\rho}$; ϕ_0 is the wave function of the pseudoscalar field; g is the corresponding constant of the fields interaction. We will further use the unit system where the fundamental constants c и $\hbar$ are equal to one.

Proceeding from (8), the equations of motion for the corresponding fields will be written in the following form:

$$\partial_\mu F_{\mu\nu} = g\partial_\mu(\phi_a\tilde{F}^{\mu\nu}); \ (\partial_\mu\partial^\mu + m_a)\phi_a = gB_0E. \qquad (9)$$

The solution (8) for a pseudoscalar field ϕ_a is

$$\phi_a^\pm(\vec{r}, t) = e^{-i\omega t}\int d^3r'\frac{1}{4\pi}\frac{\exp(\pm i\vec{k}_a(\vec{r} - \vec{r}'))}{|\vec{r} - \vec{r}'|}g\vec{B}_0\vec{E}. \qquad (10)$$

In the one-dimensional case, the decision (10) can be written as follows:

$$\phi_a^+(r, t) = iE_0(gB_0l/2k_a)F(q)e^{i(k_ax - \omega t)}.$$

Here $q = (\omega - k_a)$ is the momentum transferred to the magnetic field; $F(q) = \dfrac{\sin(ql/2)}{ql/2}$, i.e. $F(0) = 1$.

The probability of pseudoscalar boson occurrence N_a as a result of conversion N_γ of stimulating radiation quanta (photons) into pseudoscalar bosons is specified by the relation

$$P_{\gamma\to a} = \frac{N_a}{N_\gamma} = \frac{1}{4}\frac{\omega}{k_a}(gB_0l)^2F^2(q).$$

If $g \approx 10^{-10}\,\text{GeV}^{-1}$, $B = 10\,\text{T}$, $l = 1\,\text{m}$ [4–7], then

$$P_{\gamma\to a} \approx 10^{-18}.$$

In [9], Fabri – Perot matched interferometers were proposed to be used for increasing the probability of conversion (Fig. 1). If the cavity Q factor is $Q \approx 10^4$, the conversion process probability increases as follows:

$$P_{\gamma\to a} = \frac{1}{4}\frac{Q}{\pi}\frac{\omega}{k_a}(gB_0l)^2F^2(q) \approx 10^{-14}.$$

Thereby, the total probability of the conversion-reconversion process will be

$$P_{\gamma \to \gamma'} = (P_{\gamma \to a})(P_{a \to \gamma'}) \approx 10^{-28}. \tag{11}$$

Let us firstly analyze the spontaneous conversion-reconversion processes. With the exciting radiation power of about 10 Watts an argon laser operates in continuous or quasi-continuous mode of generating visible light (0.5 μm), but the number of excitatory quanta of light falling into the first cavity per one second is $N_\gamma \approx 10^{20}$. Consequently, at the second cavity output (Fig. 1), according to the relation (11), the number of the emerging photons resulted from the process of conversion-reconversion during one second is equal to $N_{\gamma'} \approx 10^{-8}$. It corresponds to the noise signals level which is below the threshold of sensitivity of the current light radiation detectors. The converted radiation intensity can be increased if the exciting radiation energy increases up to many orders of the magnitude or when the time of secondary radiation detection also increases, which significantly complicates the experimental setup. Thus, the observation of the discussed effect in the regime of the spontaneous conversion-reconversion processes with the experimental setups, presented in Fig. 1, and continuous sources of exciting radiation is unpromising.

For the stimulated conversion similarly to the SCS process (relations (6), (7)) we obtain

$$P_{\gamma \to a} = \frac{1}{4} n_a \frac{Q}{4\pi} \frac{\omega}{k_a} (g B_0 l)^2 F^2(q).$$

The transition from the spontaneous radiation regime to the stimulated one corresponds to the condition: $n_a > 1$.

To estimate a value n_a we use the relation

$$n_a = \frac{1}{4} \frac{Q}{\pi} \frac{\omega}{k_a} (g B_0 l)^2 F^2(q) n_0. \tag{12}$$

Here n_0 is the number of quanta per a field mode of the exciting radiation. To excite the stimulated processes of light scattering it is necessary to use ultrashort (10^{-8} s) or supershort (10^{-10} s) pulses of the exciting radiation [21–23]. Let us consider the case where the power density of the excitation pulse is 10^{12} W/cm^2, and its durability is 100 ps. This mode of operation, in particular, can be implemented for the second optical harmonic of the solid-state YAG : Nd^{3+} laser. Here the number of quanta per one exciting radiation field mode is $n_0 \approx 10^{14}$. According to (12) we obtain $n_a \approx 1$, i.e. under these conditions the implementation of the threshold behaviour of the stimulated radiation for conversion processes may be expected.

In the case of transition from the spontaneous radiation mode to the stimulated mode, the number of axions (the number of quanta) per an axion radiation oscillator n_a approaches to the number of quanta per an oscillator of the exciting electromagnetic radiation n_γ. If the conditions for transition to the stimulated radiation are also satisfied in the reconversion process, the intensity of light radiation at the second cavity output must be large enough to be registered by the modern detectors.

Another opportunity for the efficient increase of photon-axion and axion-photon conversion processes is the use of an extended material medium, placed in an external magnetic field, instead of cavities (vacuum resonators). Here the problem of satisfying the conditions for synchronism occurs (4), (5). This problem can be solved by adjusting the photon frequency participating in the photon-axion conversion process to the frequency of the so-called unitary polaritons of the material medium, for which the refractive index module is close to one. A very promising material for the solution are ruby crystals, an active lasing medium. With account taken of the three resonance transitions in chromium ions, the law of polariton dispersion in this crystal can be represented as follows:

$$\omega^2 = \frac{A_0^2 k^2}{\varepsilon(\omega)},$$

where c_0 is the velocity of light in a free space; $\varepsilon(\omega) = \varepsilon_\infty \prod_{j-1}^{j=3} \frac{(\omega_{lj}^2 - \omega^2)}{(\omega_{tj}^2 - \omega^2)}$.

The view of the polariton curves in ruby crystals is shown in Fig. 3. The points G_1, G_3 and G_5 are related to frequences ω_{tj} of the transverse modes, while points G_2, G_4 and G_6 are related to frequences ω_{lj} of longitudinal modes, and points $A - C$ — to unitary polaritons ($|n = 1|$). In ruby crystals there occurs a laser generation ($\lambda = 694.3$ nm) of giant (100 MW/cm^2)

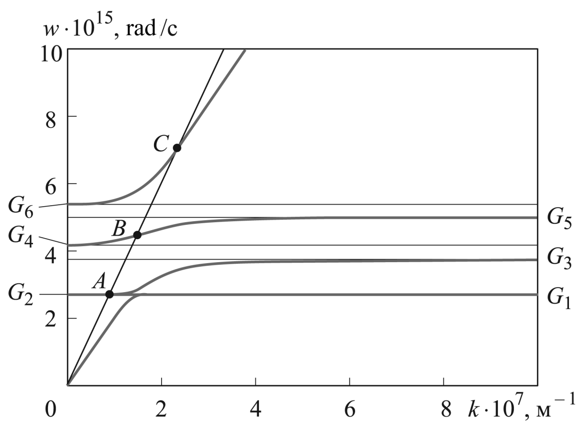


Fig. 3. View of the polariton curves in a ruby monocrystal ($Al_2O_3 : Cr^{3+}$)

pulses 10 ns long during the transition from the first excited metastable level of chromium ions (Cr^{3+}) to the ground state: $^2\mathrm{E} \rightarrow {}^4\mathrm{A}$. This transition is characterized by a very low oscillator power. The frequencies of longitudinal and transverse electromagnetic waves coincide, i.e., the wavelength of a unitary polariton coincides with the wavelength ($\lambda = 694.3$ nm) of laser transition (Fig. 3). Thus, the active medium of a ruby laser that produces radiation with frequency ω_0, can be directly used to carry out the photon-axion conversion. The basic diagram of an experimental setup for this purpose is shown in Fig. 4, *a*. The axions with frequency $\omega' = \omega_0$ must arise in the ruby crystal, placed in a magnetic field in the laser cavity with two end mirrors. After penetrating nontransparent wall *8* in the second cavity, the inverse process must occur: axion-photon conversion with the generation wave length of 694.3 nm. Radiation detector *6* is intended for the second radiation detection with frequency ω_0, which conincides with the frequency of ruby lasing.

Two more possible setups for the photon-axion conversion in ruby crystals are presented in Fig. 4, *b*, *c*. In the pattern shown in Fig. 4, *b*, the radiation from a ruby laser is delivered to a laser cell placed in a magnetic field with the other two rubies and an opaque wall. As the source of the exciting radiation, in the diagram shown in Fig. 1. *c*, the laser is used with the wavelength that corresponds to the absorption of the ruby, which results in the intensive photoluminescence in sample *2*, placed in a similar laser cell. The probability of photon-axion and axion-photon conversions in case of using this active medium (a ruby crystal) should be significantly higher than in vacuum (see Fig. 1), as the group velocity of unitary polaritons must be much less than the speed of light in vacuum (see Fig. 3). Under these conditions, the conditions are improving both to reduce the threshold of transition from a spontaneous conversion to a stimulated conversion and to increase the intensity of the signal registered by the detector.

The experimental pattern shown in Fig. 4, *d* is also considered to be promising for the photon-axion realization. The radiation from laser *9* is delivered to optical fiber *14* made of quartz fiber doped with erbium ions Er^{3+}. This material as well as the ruby crystals are used as an active medium. Radiation generation in an erbium fiber-optic laser is fulfilled in the resonance transition with the wavelength $\lambda = 1480$ nm.

In the optical fiber absorbtion spectrum there are five resonance transitions in the infrared and visible spectral ranges, corresponding to the excited states of an erbium ion Er^{3+}. The dielectric function as a function of frequency can be presented in the form of Kurosawa relation:

$$\varepsilon(\omega) = \varepsilon_\infty \prod_{j-1}^{j=5} \frac{(\omega_{lj}^2 - \omega^2)}{(\omega_{tj}^2 - \omega^2)}.$$

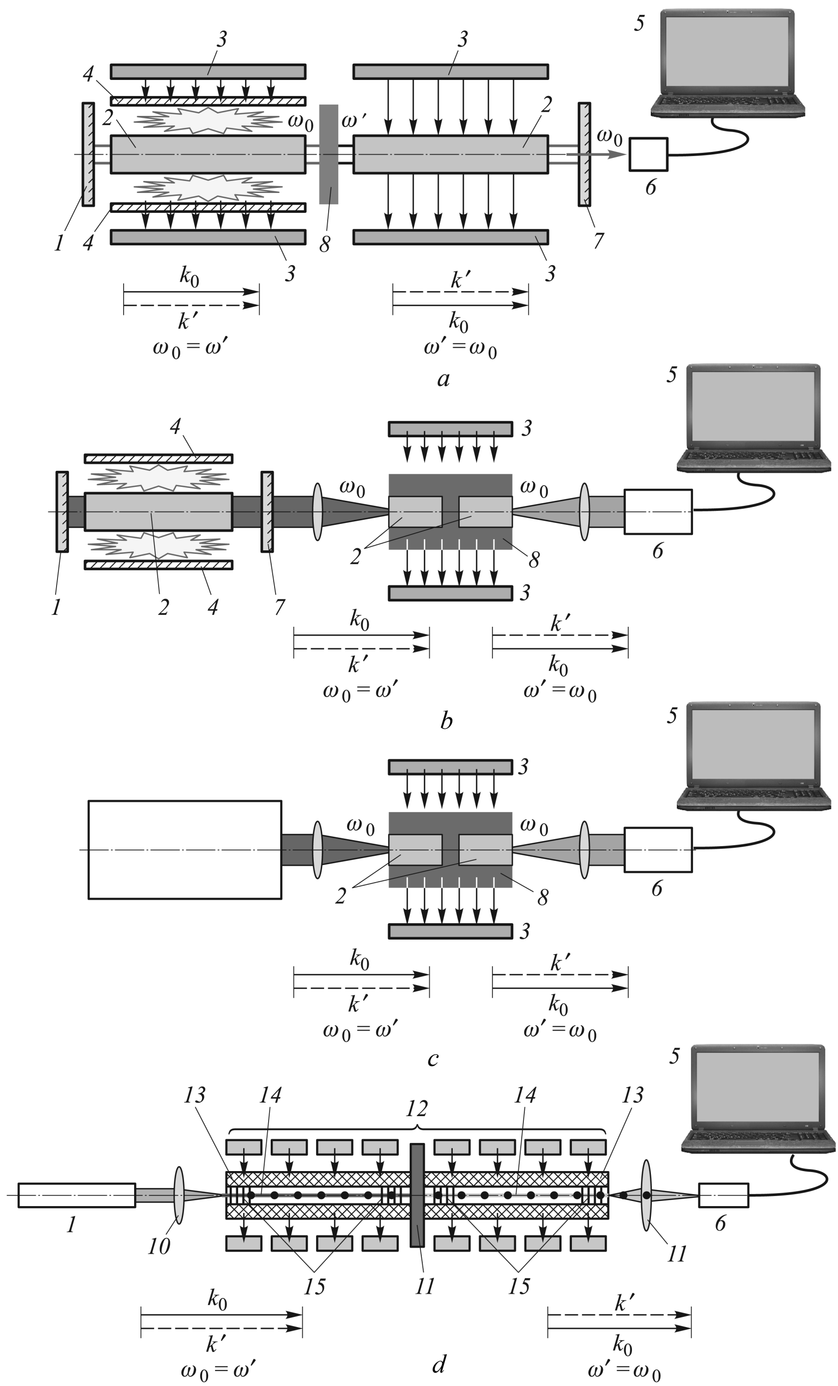


Fig. 4. Basic diagrams of photon-axion conversion realization in ruby crystals (*a*–*c*) and in a quartz fiber (*d*):
1, *7* — mirrors; *2* — ruby crystal (sample); *3* — magnet; *4* — reflector; *5* — computer; *6* — radiation detector; *8* — nontransparent plate; *9* — laser; *10*, *11* — lenses; *12* — solenoids; *13* — cladding; *14* — optical fibers; *15* — Bragg mirrors

Here ω_{tj}, ω_{lj} are frequences of resonances and nulls of dielectric permittivity. Dielectric permittivity being equal to one occurs for the so-called unitary polaritons, whose frequences ω_u can be obtained from the relation

$$\varepsilon_\infty \prod_{j-1}^{j=5} \frac{(\omega_{lj}^2 - \omega_u^2)}{(\omega_{tj}^2 - \omega_u^2)} = 1.$$

If frequence ω_0 of the exciting radiation coincides with frequency ω_u of unitary polaritons ($\omega_0 = \omega_u$), the synchronism conditions (4), (5) are satisfied automatically. The exciting laser radiation insertion into a straight quartz fiber makes it possible to obtain a high spectral intensity of the exciting radiation along the entire length of the material. The usage of Bragg mirrors *15* is the supplementary conditions for increasing the radiation intensity. If the length of the optical fiber is large enough, the probability of conversion processes increases. In certain pumping modes the processes of both spontaneous and stimulated photon-axion conversion can occur. In the second block of the experimental pattern (see Fig. 4, *d*), in the similar quartz optical fiber the axion-photon conversion occurs. The adjustment of the exciting laser radiation frequence to the unitary polariton frequencies provides the fulfilment of synchronism conditions for the processes of photon-axion conversion and inverse processes in the diagrams being considered.

The additional opportunity to improve the efficiency of photon-axion conversion can be implemented using three-dimensional photonic crystals as a conversion medium [21–29]. In these crystals unitary photons (polaritons) are present in infrared, visible and ultraviolet regions of the spectrum. The view of the dispersion curves in an artificial opal calculated for silica globules of 250 nm in diameter is shown in Fig. 5. As it can be seen in the picture the group velocities of unitary polaritons (point U) can have abnormally low values. It results in changing the probability of the spontaneous radiation processes [30] and lowering the thresholds of the relating stimulated processes [31, 32].

To illustrate the photonic crystals capabilities we developed a basic scheme of the device (Fig. 6) detecting axions which arise inside the Sun or in the center of the Earth. A photonic crystal (artificial opal) is inserted into a steel container placed in a magnetic field, in which the axion-photon conversion processes occur resulting from the solar axion transformation into unitary polaritons (see Fig. 5). The detector registers them in the direction opposite to the axions scattering direction due to the refractive index of unitary polaritons $n = -1$ (Fig. 5). A similar detector can be designed on the basis of ruby crystals or dielectric crystals with rare-earth elements.

Fig. 5. View of the dispersion curves in an artificial opal calculated for 250 nm diameter silica globules (point U corresponds to the unitary polariton $n = -1$)

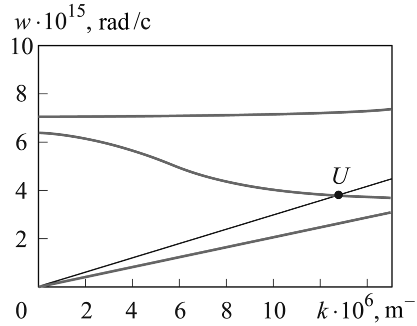
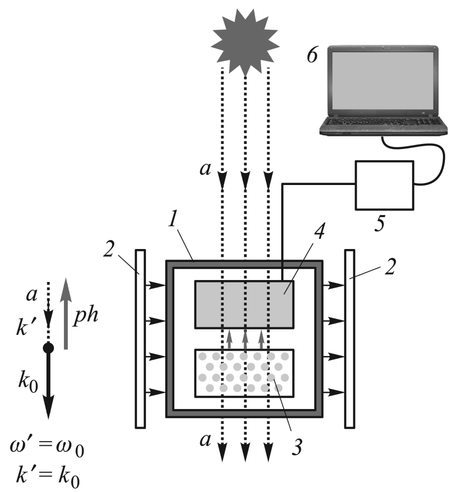


Fig. 6. Basic scheme of the device for detecting axions arising inside the Sun or in the center of the Earth using a photon crystal:
1 — closed vessel; *2* — magnets; *3* — photon crystal; *4* — radiation detector; *5* — amplifier; *6* — computer



“Cold” axions detection in the microwave spectral region. The problem of slow (“cool”) axion registration involves detecting the microwave radiation in a strong magnetic field with the quantum energy (0.001. . . 1.0 meV) coinciding with the energy of axions. With the imposition of a sufficiently strong external magnetic field (1. . . 10 T), the microwave photons must arise in the closed isolated cavity as a result of the “cold” (slow) axions conversion into photons.

The possibility of experimental detection of axions the laboratory using the Josephson effect [35–38] has recently been analyzed. A basic diagram of a microwave radiation detector for the axion-photon conversion using the non-stationary Josephson effect is shown in Fig. 7. Detection of the so-called Shapiro steps in the volt-ampere characteristic provided the opportunity of obtaining [39] the estimates of the axion rest energy (0.11 meV) and of their density (0.05 GeV/cm^3) in the surrounding space.

Other principal schematics of detectors of microwave photons arising from the axion-photon conversion, based on sensitive detectors of microwave radiation, are presented in Fig. 7, b, c. In this case a high-Q cavity is supposed to be used consisting of two niobium mirrors (*8*, *10*), one of which has a small hole. The cavity is placed in a cryostat for suppressing

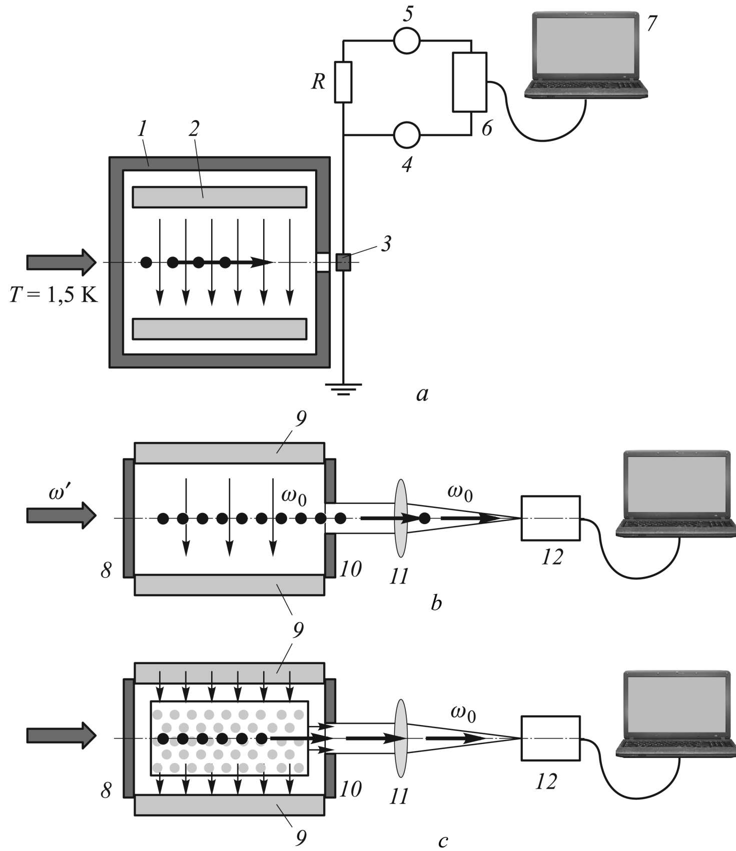


Fig. 7. Basic diagram of a microwave radiation detector for axion-photon conversion using the non-stationary Josephson effect (*a*), basic diagrams for observing the conversion of axions into microwave radiation in a cavity (*b*) containig a photon crystal with large diameter globules (*d*):
1 — screen; *2* — magnets; *3* — Josephson junction; *4*, *5* — current and voltage meters; *6* — signal analyzer ; *7* — computer; *8*, *10* — niobium mirrors; *9* — magnets; *11* — teflon lens; *12* — microwave radiation detector

the thermal radiation. The diagram in Figure 7, *b* shows an unfilled cavity. Using teflon lens *11*, the microwave radiation is directed to a highly sensitive detector.

The cavity filling up with photon crystal or some suitable metamaterial (Fig. 7, *c*), having a spectral position of the stop zone controlled by an external magnetic field, with this stop-zone located in the microwave spectral region, will make it possible to slow down the flow of microwave photons arising in the cavity and, consequently, to raise the spectral intensity of microwave radiation.

The energy density of the dark matter in the near-Earth space is $\rho \approx 10^{-10}\,\text{J/cm}^3$. Thus, the energy of the dark matter focused in the volume $V = 1\,\text{m}^3$, is $10^{-4}\,\text{J}$. If we proceed from the hypothesis that the clouds of the dark matter in the near-Earth space consist mainly of axions, the intensity of the microwave radiation generated by axion-photon conversion of decays is determined by the probability of these decay processes that depend on the magnetic field created by the superconducting solenoids. Experimental monitoring of axion-photon conversion will allow to estimate the probability of such processes and answer the question about the possibility of axion generation in a laboratory setting.

Conclusion. The ways of optimization of experimental setups for detecting "hot" and "cold" axions, assumed to be the elementary particles of the dark matter have been proposed. To generate "hot" axions pulsed sources of the laser radiation are suggested to be used, with high spectral intensity of the radiation in the visible or ultraviolet ranges. It provides a transition from spontaneous axion-photon conversion to stimulated processes similar to light SCS processes. The expected axion rest mass corresponds to the microwave spectral region 0.001... of 1.0 MeV. A highly sensitive spectrum analyzer based on the Josephson non-stationary effect is proposed as a detector of microwave photons generated by the decay of "cold" axions. To increase the intensity of microwave radiation resulting from the axion-photon conversion into the microwave cavity, it is proposed to introduce metamaterials or photon crystals that slow down the microwave photons to velocities significanly lower than the speed of light. The increase of the microwave radiation intensity is stipulated by the increase of the relating photon states while the group velocity of microwave photons becomes significantly lower than the speed of light in vacuum ($v \ll c$) [29-32]. As a medium that slows down microwave photons arising from the axion-photon conversion in the cavity we proposed to use the folloing: globular photon crystals [30–32] with a forbidden band in the microwave range; metamaterials with a negative refractive index and a low group velocity of the electromagnetic waves; ferroelectrics with a high-Q soft mode, etc.

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