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Axions in a Dispersed Medium: Light Scattering, Vavilov-Cherenkov Radiation

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I. Introduction

What happens to photons of laser radiation whose energy differs from the energy of the inter-level electronic transitions of atoms of the substance under study. According to Bohr and Einstein, the traditional scheme of interaction between radiation and matter includes the following processes: 1) resonant absorption of radiation, 2) spontaneous radiation, 3) resonant stimulated radiation. In the absence of resonance between the pumping frequency and the frequencies of electronic transitions in atoms alloying a dispersed medium, the interaction of radiation and matter is carried out due to the annihilation of pairs of pump radiation photons, the birth of axions and their subsequent decay into new photons whose energy differs from the energy of the pump photons. If in atomic vapors in the resonant case one photon is required for the transition of an electron from the ground level S to the excited P, then in the non-resonant case such a transition is possible due to the annihilation of a pair of photons.

II. Axions in A Dispersed Medium

First of all, we should recall the definition of a dispersed medium (DM). In DM, the doping (alloying) phase in the form of small formations is distributed in the main volume of the continuous phase. Continuous phase DM - glass, liquid, air, vacuum. The second is the doping component DM, weighted in the volume of the continuous phase: these are atoms, molecules or nanoparticles of an element alloying the medium. Air, water, organic liquids, atomic vapors of alkali metals in a vacuum cuvette are also DM. When a laser beam propagates in DM, its spectral and angular characteristics change.

The aim of the work is to analyze the processes accompanying the propagation of a laser beam in DM in the absence of resonance between the pumping frequency and the frequencies of electronic transitions. The high density of photons in the laser beam and the high intensity of the electromagnetic field of the atomic nuclei of the element selected for DM doping cause the possibility of annihilation of photon pairs, which leads to the birth of axions. Their decay determines the features of the spectral and angular structures of radiation at the exit from the medium.

What happens to the photons of laser radiation in DM? What do we have at the output of DM? How does the radiation spectrum change?

Only in a vacuum does the propagation of light radiation obey the laws of wave optics. In this case, laminar collisionless movement of photons in the beam occurs. In the case of propagation of light radiation in the DM, due to the interaction of the photons of the beam with the electron shell of the atomic nuclei of the atoms alloying the medium and the atoms of the medium itself, the laminar motion of the photons is disrupted, the velocity of the photons meeting the electron shell of the atoms alloying the medium slows down. This circumstance leads to interphoton collisions, interphoton interaction, annihilation of photon pairs with the birth of axions in the strong field of the atomic nucleus [1].

According to the works [2] of the American physicist Primakov (HENRY PRIMAKOFF), annihilation (fusion) of two quanta (photons) in the electro-magnetic field of the atomic nucleus can lead to the birth of the axion - A•. Leaving the atom, the axion decays into two new quanta (photons) – the forward and reverse Primakov effects:

$$h\nu + h\nu = A\bullet = h\nu_{ij} + h\nu_{0j} \qquad (1)$$

where:

$h\nu$ is the energy of quanta (photons) of light radiation used to pump DM,

ν is the frequency of this radiation.

Just note that the Primakov effect may be direct or reverse. In the second case, when you turn off the field of the atomic nucleus decays of the axion to two photons.

$h\nu_{ij}$ - is the energy of quanta (photons) of radiation from one of the many components of the broadened spectrum of radiation scattered by the medium, or one of the many components of the photoluminescence spectrum, or one of the many components of the angular spectrum of radiation at the output of the investigated DM, (determined by the difference between the energy of the virtual level - *i* and the energy of atomic level *j* ; The energy of the virtual level is equal to the sum of the energies of two pump photons. The energy of the virtual level – *i* can be greater or less than the

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energy of the electronic levels of the doping element under study.

$h\nu_{0j}$ - is the energy of the quanta absorbed by the medium; the energy of this quantum is equal to the energy of the electron transition from the ground level to the excited one .The number of levels *j* in the spectrum of the atom of the element under study is infinite.

What determines the energy of the virtual level? The energy of the virtual level - *i*can be greater or less than the energy of the electronic levels of the alloying element under study.

Since the birth of the axion and its existence presupposes the presence of strong electromagnetic fields, in our case, the fields of the atomic nucleus, neither Rayleigh scattering on solid particles nor Mandelstam—Brillouin scattering by condensed media (solids and liquids) as a result of its interaction with the intrinsic elastic vibrations of these media will be considered by us. We will also not take into account the scattering of light by fluctuations in the density of the medium (small local deviations of the density from its average value), with which, as is commonly believed in the wave model, the scattering process is associated.

a) Forced electron raman scattering (EFRS) in atomic potassium vapors

It was experimentally possible to register the process of annihilation of photonic pairs and the decay of axions in the case of almost resonant interaction of laser radiation with atomic potassium vapor in the frequency range, where the normal dispersion and where the refractive index is greater than one. These conditions in atomic potassium correspond to the electronic transition $4S_{1/2}$-$4P_{3/2}$(Fig.1). We will consider a region of the spectrum where interphoton interaction is possible, annihilation of photon pairs, the birth of axions and their decay are possible.

As a rule, the energy of laser-pumped photons does not coincide with the inter-level energy interval of any of the electronic transitions of both the alloying atom and the atoms and molecules of the doped medium. A frequency-tunable parametric light generator (PLG) was used as a pumping laser in [3], which made it possible to study changes in the frequency and angular structure of the spectrum at the output of the cuvette in atomic pairs of cadmium in the frequency range of the main doublet. The radiation power of PLG was 50...500 kW with a pulse duration of 10...15 ns. The temperature of potassium vapors in the cuvette was maintained in the range of 250...300°C. The radiation spectrum at the outlet of the cuvette was recorded on a spectrograph with a dispersion of 6 A°/mm. Recall the frequencies corresponding to potassium doublet lines: low-frequency doublet line $4S_{1/2}$-$4P_{1/2}$: ν_{02} = 12989 cm^{-1}, high-frequency doublet line $4S_{1/2}$-$4P_{3/2}$: ν_{01} = 13046 cm^{-1}. This experiment is described in detail in [3-5].

In the first spectrogram (Fig. 1a), the pump radiation frequency is $\nu \approx$ 13020 cm^{-1}, less than the transition frequency $4S_{1/2}$-$4P_{3/2}$. In this case, with a shift to the low-frequency region of the spectrum relative to the pumping frequency -ν, a resonant electron forced raman scattering (EFRS) line is recorded at the output of the cuvette, the frequency of which is indicated by ν_3:

$$\nu_3 = 2\nu - \nu_{01}. \qquad (2)$$

Calculated according to the ratio (2), the frequency value ν_3 coincides with the experimental value.

The energy of photons of radiation at the frequency $\nu_3$can be obtained from the ratio:

$$h\nu_3 = 2h\nu - h\nu_{01}. \qquad (3)$$

In relation (3) there is a term $2h\nu$, indicating the addition of two pump radiation photons (annihilation of which in the field of the atomic nucleus leads to the appearance of an axion - the Primakov effect). In the field of the same atomic nucleus, in an elementary act, an axion whose energy is equal to $2h\nu$, decays into two photons (quanta) – the reverse Primakov effect.

Laser radiation (frequency $\nu \approx$ 13020 cm^{-1}) transfers electrons from the ground level $4S_{1/2}$to the virtual one, the energy of which is determined by the value E = 2 $h\nu$ with the formation of an axion. The energy of the virtual level in the atom is counted from the main level. When the axion decays, the electron transitions from the virtual level 2 $h\nu$to the level $4P_{3/2}$.

The radiation line of the pump – ν at the outlet of the cuvette is widened. The question of broadening the laser radiation lines in a dispersed medium was considered in [1]. The broadening of the lines is associated with the annihilation of photon pairs, the appearance of axions and their decay. Accordingly, with the pump – ν radiation line at the output of the cuvette, the EFRS - ν_3 line is also widened, which follows from the ratio (2).

In the spectrogram (Fig. 1a), in addition to the pump – ν radiation and the radiation at the frequency of ν_3, there is a complex spectral structure in the anti-stokes region of the spectrum relative to the pump (from νtoν_{as}), reflecting the change in the divergence (angular spectrum) of radiation at the output of the cuvette.

The features of the spectrum associated with the change in the angular spectrum of radiation at the output of the cuvette at the frequencies ν, ν_3, ν_{as}, we will consider in the next section.

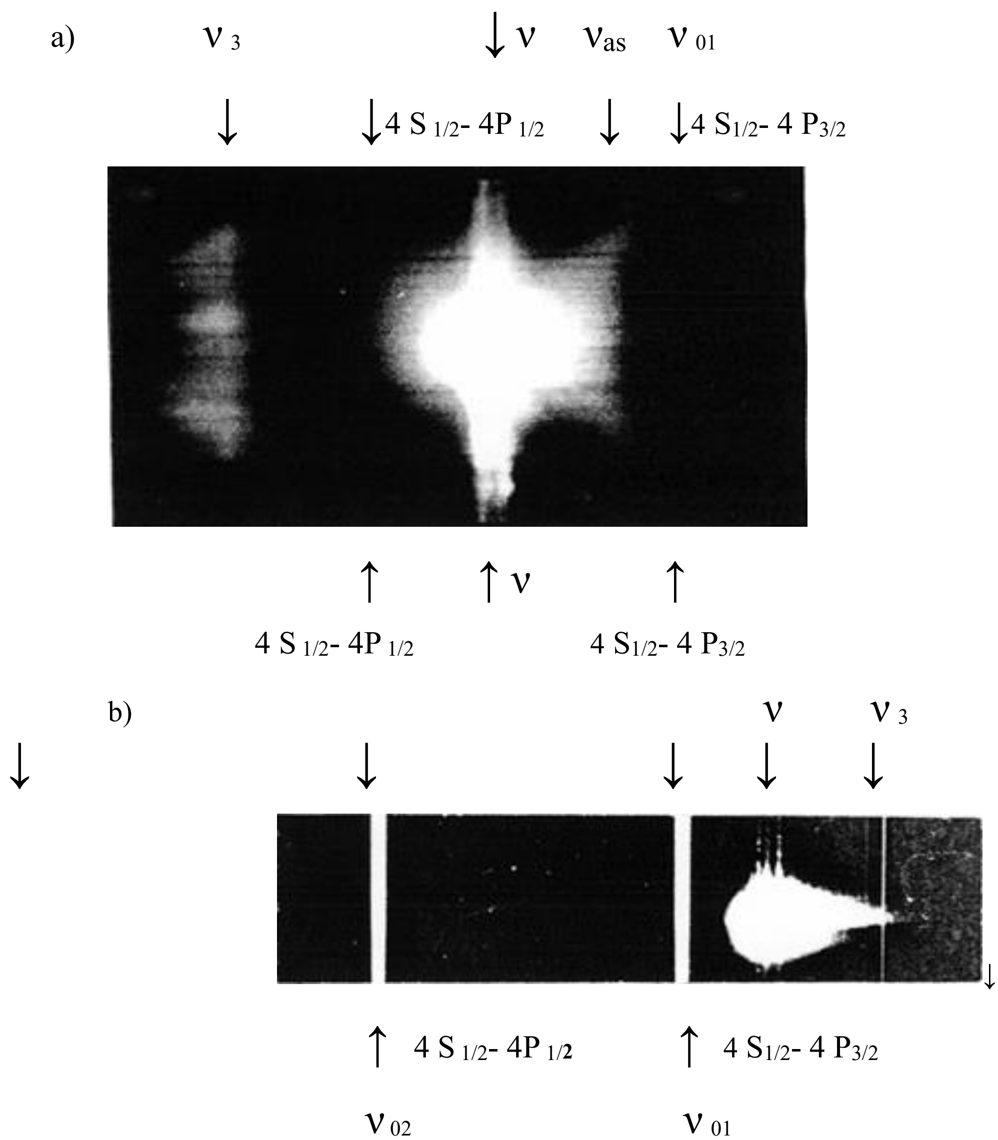

Fig. 1: Spectrograms illustrating the role of axions in the propagation of laser radiation pulses through a cuvette with potassium vapor in the frequency range of the main doublet 4 $S_{1/2}$- 4 $P_{1/2,\ 3/2}$. ν is the frequency of laser radiation; ν_{01} is the frequency of the transition line $4S_{1/2}$–$4P_{3/2}$ (13046 cm^{-1}); ν_{02} is the frequency of the transition line 4 $S_{1/2}$- 4 $P_{1/2}$, (12986 cm^{-1}); ν_3 is the frequency of the forced electron raman scattering line.

$\nu_3 = 2\nu - \nu_{01}$ (the value of 2ν reflects the process of annihilation of two photons with the formation of an axion, during the decay of which photons appear at the frequency ν_3). The reference lines of the doublet ν_{02}, ν_{01} on the spectrogram 1 b) were obtained using a spectral lamp. In the second spectrogram (Fig. 1b), the pump radiation frequency $\nu \approx$ 13070 cm^{-1} is shifted to the anti-Stokes region relative to the frequency of the transition line $4S_{1/2}$-$4P_{3/2}$. In this case, we have a broadening of the frequency spectrum. On a spectrogram with a shift to the high-frequency region of the spectrum relative to the pumping frequency -ν, a weak line of resonant electron forced raman scattering (EFRS) is also recorded at the output of the cuvette, the frequency of which is indicated by ν_3.

Thus, the EFRS process observed at small detunings of the pump frequency from the resonant transition frequency in potassium vapor during the absorption of two photons in an elementary act with the formation of an axion is accompanied by the transfer of electrons from the main level $4S_{1/2}$ to the level $4P_{3/2}$. What distinguishes an almost resonant process from a resonant one. In the case of resonant pumping, the transfer of an electron from the $4S_{1/2}$ level to the $4P_{3/2}$level is carried out due to single-photon absorption.

b) The structure of the angular spectrum of the laser beam, behind the output window of the cuvette with atomic potassium vapor

When considering the angular spectrum of the laser beam at the output of the cuvette, in the frequency range close to the frequency of the resonant transition, self-action processes (self-focusing, self-focusing) take place [3,5], which do not imply a change in the structure of the frequency spectrum of laser radiation at the output of the medium. The results of the observation of these processes are presented in [6,7]. The effects of self-action are associated with an uneven, Gaussian distribution of the radiation intensity over the cross-section of the laser beam. Near the frequency of the resonant transition, the refractive index of the medium (in our case of atomic potassium vapors) in the electromagnetic field of the laser beam depends on the intensity distribution over the cross-section of the beam. This circumstance explains the change in the wavefront of the beam, leading either to self-focusing ($\nu<\nu_{01}$) or to self-focusing ($\nu>\nu_{01}$).

Let us turn once again to the spectrograms presented in Fig. 1. The optical scheme of their registration is constructed in such a way that frequencies are recorded on the spectrograms outside the output window of the cell in the horizontal direction relative to the axis of the laser beam, and in the vertical direction the radiation propagating at an angle to the axis of the laser beam is recorded. To do this, a lens was installed between the output window of the cuvette and the slit of the spectrograph, displaying the output window of the cuvette on the slit of the spectrograph. The slit displays the diameter of the base of the cone of light radiation resting on the exit window of the cuvette. Such an optical scheme makes it possible to register the frequency spectrum of the cone components of radiation scattered in potassium vapor at an angle to the optical axis.

Consider the features of the angular spectrum of radiation at the output of the cuvette in the case when the radiation frequency of the pump is $v< v_{01}$. In this case, the structure of the angular spectrum at the frequencies v , v_3, as well as in the frequency range between v and v_{as} is recorded on the spectrogram.

First of all, we note (Fig.1a) that at the frequency v outside the output window of the cell, the central spot corresponds to the initial direction of propagation of the laser beam. The radiation shifted up and down relative to the optical axis of the frequency v at the same angle indicates that a divergent cone of radiation is formed in the cuvette, the base of which is the output window of the cuvette.

In the considered region of the spectrum, the refractive index is greater than one. In such an environment, the speed of photons outside the laser beam is equal to the phase speed of light at the frequency $v = c / n$. When a laser beam propagates in atomic potassium vapors, first of all, the populations of the 4*S* and 4*P* levels align on the beam axis, which changes the refractive index. Under these conditions, it is equal to one. Therefore, along the beam axis, both photons and axions can propagate at the speed of light - c. According to the definition, the propagation of particles (in our case axions) at the speed of light in a medium where photons move at the phase speed of light is accompanied by Vavilov-Cherenkov radiation. Two spots shifted up and down at the same angle indicate the birth of such radiation in a cuvette with potassium vapors.

Let's return to Fig.1a. At the frequency ν_3 we have a similar picture – a central spot and components scattered at an angle up and down. According to relation (2), their appearance is caused by the process of three-photon electron scattering, which repeats the structure of the radiation spectrum at the frequency v for the frequency v_3.

Finally, we need to explain the structure of the angular spectrum in the frequency range from v to vas. In [8] this structure was called "mustache". It is interesting because there are no pump photons on the beam axis near the frequency v_{as}. In [6], it was proposed to use nonlinear polarization to interpret this structure.. The absence of pump radiation photons on the optical axis does not exclude the presence of axions there – particles propagating in the medium at the speed of light and responsible for the Vavilov-Cherenkov radiation cone. This interpretation of the nature of the "mustache" strictly corresponds to the definition of Vavilov-Cherenkov radiation, according to which it is the beam of particles (axions), moving at the speed of light that, causes this radiation.

c) Propagation of laser radiation in transparent media (air, water); heating of the medium

In the case of propagation of laser beams in transparent media (air, water), light scattering occurs, which can be explained by the decay of axions in the electromagnetic fields of nitrogen, oxygen and hydrogen atoms. Let us analyze the case of the propagation of a light beam in a medium, considered in [9]. "Let's assume that we illuminate a transparent medium in complete darkness, for example, clean water, with an intense laser beam. Even if the medium does not contain any impurity particles, the trajectory of the beam in the medium may become slightly noticeable even when observed in directions that do not lie in the plane of incidence…We must... reveal... the origin of this weakly scattered light in all directions, which is superimposed on a more intense unidirectional beam." The authors [9] believe that fluctuations in the density of the medium (in this case, water) are responsible for the scattering of light in all directions. However, this explanation is not enough, part of the energy of the laser beam is spent on heating water. Scattering by density fluctuations does not lead to heating of water.

In our opinion, it is natural to assume that when axions decay into two photons at a frequency ν_{ij}, radiation scattering occurs in all directions (angle 4 π steradian). It is possible to explain the heating of the medium, which is associated with the process of non-radiative relaxation to the ground level of electrons trapped at the excited level when the medium absorbs the second quantum of the decayed axion in accordance with the ratio (1).It can also be assumed that similar processes occur in the earth's atmosphere under the influence of solar radiation; solar photons annihilate in the earth's atmosphere with the formation of axions, the decay of which is associated with the heating of the atmosphere and possibly photons at frequencies ν_{ij} contribute to the blue color of the sky.

Let's add a few remarks to the question of what role axions play in laser technology. We found out that in the absence of resonance between the pump radiation frequency and electronic transitions in the medium, the axion decay involves the transfer of thermal energy to the medium and its heating due to the process of non-radiative relaxation. Therefore, cooling systems are used for heat removal in solid-state lasers, and active medium pumping systems are used in dye lasers.

The process of scattering radiation in all directions (angle 4 π steradian) in [10] was used to illuminate the laser mirror with the reversal of the wave front. Such a laser works in the presence of phase in homogeneities in the resonator.

III. Conclusion

According to Bohr and Einstein, the traditional scheme of interaction between radiation and matter includes the following processes: 1) resonant absorption of radiation, 2) spontaneous radiation, 3) resonant stimulated radiation. In the absence of resonance between the pumping frequency and the frequencies of electronic transitions in atoms alloying a dispersed medium, the interaction of radiation and matter is carried out due to the annihilation of pairs of pump radiation photons, the birth of axions and their subsequent decay into new photons whose energy differs from the energy of the pump photons. Let's list the processes for which the use of the axiope model seems natural. This is the scattering of light in dispersed media, including scattering in air by a solid angle equal to 4 π steradian. This is resonant forced raman scattering of electrons (EFRS). The decay of the axion into two quanta, whose energy differs from the energy of the pump radiation photons, explains the heating of the medium by the incident pump radiation. This is also the photoluminescence process considered in [11].

Finally, an axion is a particle generating a cone of Cherenkov-Vavilov radiation under specially created experimental conditions.

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