CONTINUOUS GENERATION OF A GRAVITATION BEAM

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We analyze different schemes for generating and detecting gravitational scalar and tensor waves with the aid of electromagnetic and acoustic generators under laboratory conditions. For the generation of coherent continuous gravitational waves in the optical range, we propose to use the superradiant states of quantum systems. Schemes are proposed for the detection of zero-point oscillations of the gravitational field.

1. INTRODUCTION

WE have shown earlier[1-3] that the excitation by means of lasers of collective coherent states in the system of N particles having a discrete spectrum can be used to generate and receive coherent gravitational rays (GR) up to optical frequencies and above.

It was proposed in those papers to excite the GR in the form of a sequence of powerful short pulses with duration on the order of the time of transverse relaxation T_2^* of the active particles. In view of the fact that the technique for obtaining exciting pulses of duration $\Delta t \leq T_2^*$ is complicated, and a tremendous number of such pulses is necessary for the excitation of a noticeable number of gravitons, it is of interest to discuss the possibility of generating GR in the continuous regime.

In this paper we propose to use for the generation of continuous GR the graviton analog of stimulated optical[4] and phonon[5] induction. The phenomena of Bloch[6], optical, phonon, and any other stimulated induction consist in the following. We consider a quantum system with an unperturbed Hamiltonian $\mathcal{H}_0$. We describe the interaction of this system with the external physical fields in terms of the emission and absorption of multipoles (electromagnetic, elastic[5,6], mass[1-3], spin-wave[7], etc.). We break up the operators of the multipoles into parts which possess in the $\mathcal{H}_0$ representation: a) only diagonal matrix elements (longitudinal components), and b) only nondiagonal matrix elements (transverse components). The excitation of stimulated induction consists in producing, by means of an external generator, stationary coherent oscillations of the transverse components of the multipoles. The latter leads to the emission by the system of coherent fields, the physical nature of which can differ from the nature of the exciting field. We shall call this signal stimulated induction, in analogy with the known nuclear-magnetism case[6]. There exists a rule, which determines whether a given external generator can excite oscillations of coherent components of a given multipole (see[8]): to this end, the multiple commutator $[\ldots[[B, A]_- \ldots A]_-$ should have diagonal matrix elements; here A is the operator of the interaction of the external generator with a system $\mathcal{H}_0$, and B is the operator of the radiating multipole. Because of this we can, for example, excite oscillations of quadrupole moments through dipole transitions. Unlike the pulsed case[1-3], in the stationary regime the intensity of the stimulated-induction signal depends on both the transverse and longitudinal relaxation times T_2^* and T_1; the mechanism of transverse relaxation violate the coherence of the oscillations of the radiating elementary dipoles, thereby decreasing the intensity of the signal; on the other hand, the longitudinal relaxation replenishes all the time the number of multipoles, which can again be excited in the coherent state.

According to the existing concepts[9], in order to generate gravitational waves it is necessary to excite oscillations of mass quadrupole moments. Since the intensity of the radiation of the gravitational waves by an isolated quadrupole is proportional to the sixth power of the circular frequency of the oscillations ($I_g \sim \omega_g^6$), it is important to find a method of exciting the mass quadrupoles at optical and γ-ray frequencies. Such a possibility is based on the fact that excitation of oscillations of electric multipoles by an external electromagnetic field leads also to oscillations of the mass multipoles. Therefore lasers can be used for the excitation of mass quadrupoles in the stimulated-induction regime. To excite GR in the range $10^{12} \leq \omega_g \leq 10^{14}$ rad/sec, we can use the rotational and vibrational levels of the molecules, in the range $10^{14} \leq \omega_g \leq 10^{17}$ rad/sec we can use the electronic levels of atoms and molecules, while in the γ-ray frequency range we can use intranuclear transitions.

In the considered range of frequencies ω_g, the generation of GR is effected by a system of $N \gg 1$ mass quadrupoles, the linear dimensions of the system greatly exceeding the wavelength λ_g of the gravitons. This leads to $I_g \sim \lambda_g^2 \omega_g^6$ as a result of interference effects. If we further recognize that for the reception of the GR it is necessary to record at least one quantum, the efficiency of the discussed method of generation of reception of GR increases with frequency like ω_g^3.

In media in which the refractive index for electromagnetic waves is $n > 1$, we have, upon excitation of GR in the single-quantum regime, $I_g \sim \lambda_g^4 \omega_g^6$, owing to the difference between the wave vectors $\mathbf{k}_e$ of the photons and $\mathbf{k}_g$ of the gravitons with the same frequency. To avoid an additional decrease of I_g by a factor λ_g^2, it is necessary to excite the GR in the two-quantum regime using two lasers, which enables us to make the effective $\mathbf{k}_e$ equal to $\mathbf{k}_g$. The equality $\mathbf{k}_e = \mathbf{k}_g$ in single-quantum excitations can apparently also be attained in inverted systems. We note that in dense gases $n \cong 1$ and in them, with sufficient accuracy, we have $\mathbf{k}_e = \mathbf{k}_g$.

A serious obstacle to the experimental realization of GR generation is the powerful electromagnetic radiation, which of necessity must accompany the GR. To decrease the intensity I_e of this radiation we can use the following properties of a system of multipoles: 1) if the system is excited with the aid of two lasers producing effective $\mathbf{k}_e = \mathbf{k}_g$, then the intensity of electromagnetic radiation at the frequency ω_g decreases by a factor λ^2 compared with the case of single-quantum excitations; 2) one excites the system in electromagnetic resonators which have no mode at the frequency ω_g, at least in the direction of $\mathbf{k}_g$, and this should in general suppress the coherent spontaneous electromagnetic radiation with $\mathbf{k}_e = \mathbf{k}_g$; 3) the direction of the effective $\mathbf{k}_e = \mathbf{k}_g$ should coincide with one of the minima of the intensity of the spontaneous emission of the isolated electric quadrupole.

The scheme for the reception of GR is the inverse of that proposed above: the GR and the auxiliary elimination excite coherent oscillations of electromagnetic multipoles leading to generation of an optical ray, the frequency and direction of which are determined by the GR and by the pump. It is important here that the two-quantum regime of GR reception makes it possible to compensate for the small power of the graviton flux, at the expense of the power of the pump generator. The graviton ray, as it were, "controls" the direction of the radiation of the light ray of the receiver, and the radiation energy is drawn from the pump.

We develop in this paper a quantum-statistical theory of generation of GR with the aid of lasers at the electronic levels of atoms and molecules (Π_{el}), at the rotational and vibrational levels (Π_{rv}), and at the Landau levels. The parameters of the corresponding generators and the expected intensities I_g are listed in Table I. The parameters of the receivers and the intensities of the light ray at the receiver output are listed in Table II. Two cases are considered.

1) Direct method: reception of GR from a generator located at a certain distance from the receiver. The illumination is provided by both a laser and an acoustic field.

2) Indirect method: one receives photons or phonons created in two-quantum processes, in which the zero-point oscillations of the graviton field take part. The system is excited by a laser.

Table I. GR generation power in the stimulated induction regime.

Nature of levels |1> and |2>	ω_g, rad/see	m_0, g	Q_0, cm^2	V, cm^3	$V^{-1}N$, cm^{-3}	S, cm^2	$I_{coh}(\omega_g)/\sin^2\theta_2$, erg/sec
Π_{el}	10^{16}	10^{-27}	10^{-16}	10^6	10^{21}	10^3	10^{-12}
Π_{rv}	10^{13}	10^{-22}	10^{-15}	10^6	10^{23}	10^3	10^{-10}

Note. Π_{el} – electronic levels, Π_{rv} – rotational or vibrational levels of molecules.

2. GENERATION OF THE GRAVITATIONAL RAY

We consider a system of N identical particles with a discrete spectrum. We denote by $|1\rangle$ the ground state of the isolated particle, and by $|2\rangle$ one of its excited levels with energy $E_2 - E_1 = \hbar\omega_0$. The unperturbed spectrum of such a subsystem is described by the operator

$$\mathcal{H}_0 = \hbar\omega_0 \sum_{j=1}^{N} R_3{}^j,$$

and its interaction with the external generators with effective wave vector $\mathbf{k}$ and effective frequency ω can be represented in the form

$$\mathcal{H}_r = A_\mathbf{k} R_{\mathbf{k}+} + A_\mathbf{k}{}^+ R_{\mathbf{k}-},$$

$$R_{\mathbf{k}\pm} = \sum_j R_\pm{}^j \exp(\pm i\mathbf{k}\mathbf{r}_j), \quad R_\pm{}^j = R_1{}^j \pm iR_2{}^j,$$

$$[R_+{}^j, R_-{}^j]_- = 2R_3{}^j, \quad [R_3{}^j, R_+{}^j]_- = R_+{}^j, \quad [R_3{}^j, R_-{}^j]_- = -R_-{}^j, \quad (1)$$

where R_d^j is the component of the operator of the effective spin $R = 1/2$, $\mathbf{r}_j$ is the radius vector of the particle j, and A_k is an operator describing the interactions with the external generator.

We denote by $I_0(\mathbf{k}_\xi)$ the intensity of the spontaneous emission of the isolated multipole of type ξ per unit solid angle in the direction $\mathbf{k}_\xi$, where $\mathbf{k}_\xi$ is the wave vector of the generated field. The radiation intensity of the system of N multipoles of type ξ in the regime of

Table II. Power at the receiver output in the detection of a gravitational ray in various reception methods

Methods of GR reception	Nature of levels |1> and |2>	Receiver parameters							Power at reciever output erg/sec
With phono pumping		ω_g	$G_{\eta\zeta s_1 t}$ (erg)	$U^0_{s_1 t}$	ω_{pn}	$\lvert\omega_\xi - \omega_{pn} \mp i\Gamma_\xi\rvert$	$\Delta\omega$	T_2^*	
	Π_{el}	10^{16}	10^{-10}	10^{-5}	10^{11}	10^7	10^7	10^{-6}	10^{-13}
	Π_{rv}	10^{13}	10^{-10}	10^{-3}	10^8	10^7	10^7	10^{-6}	10^{-11}
With phono pumping		ω_g	$\lvert\omega_\Phi - \omega_{2\pi} + i\Gamma_\Phi\rvert$		$\lvert\omega_\xi - \omega_{1\pi} + i\Gamma_\xi\rvert$		$\lvert\langle\xi\lvert p^j\rvert\zeta\rangle\rvert$		
	Π_{el}	10^{16}	10^{16}		10^7		10^{-18}		10^{-7}
	Π_{rv}	10^{13}	10^{13}		10^7		10^{-18}		10^{-3}
Phono-graviton scattering (second stage)		$\omega_э^{(2)}$	$\Delta\omega_{(2)}$	T^*_2	$\omega_\alpha - \omega_{pn}$	$\omega_\alpha - \omega_{pt}$	$I_{coh}(\omega_{pn})$		
	Π_{el}	$5\cdot10^{15}$	10^9	10^{-8}	10^{15}	10^{15}	10^{-18}		10^{-3}
	Π_{rv}	$5\cdot10^{12}$	10^9	10^{-8}	10^{12}	10^{12}	10^{-18}		10^5

Note. The values of the remaining parameters needed for the calculation of the power at the receiver output were taken from Table I. E_{1r}, E_{2r}, $E_2 \sim 10^7$ V/cm; ξ, α, and Φ are the indices of the intermediate states of the impurity.

continuous stimulated induction, per unit solid angle in the direction $\mathbf{k}_\xi$, when excited by a generator with Hamiltonian H_r, is calculated from the formula

$$I(\mathbf{k}_\xi) = I_0(\mathbf{k}_\xi)\,\mathrm{Sp}\,\{\rho(\mathbf{k}) R_{\mathbf{k}_\xi +} R_{\mathbf{k}_\xi -}\}, \qquad (2)$$

where $\rho(\mathbf{k})$ is the density matrix of the system, calculated with allowance for its evolution under the influence of $\mathcal{H}_r$[9,10].

Let the system be irradiated by two generators with wave vectors $\mathbf{k}_1$ and $\mathbf{k}_2$ and of frequencies ω_1 and ω_2. Then calculations, in accord with[1,2], lead to the following formula for the intensity of the stimulated gravitational induction (SGI):

$$I(\omega_g) = \int d\Omega I(\mathbf{k}_g), \quad I(\mathbf{k}_g) = I_0(\mathbf{k}_g)\frac{N}{2}\Big\{1 - \cos\theta_1 \operatorname{th}\Big(\frac{\hbar\omega_g}{2k_B T}\Big)$$
$$+ \frac{1}{2}\sin^2\theta_2 \operatorname{th}^2\Big(\frac{\hbar\omega_g}{2k_B T}\Big) N^{-1}\sum_{j\neq l}^{N}\exp[i(\mathbf{k}_g - (\mathbf{k}_1 + \mathbf{k}_2))\mathbf{r}_{jl}]\Big\}, \qquad (3)$$

where $d\Omega$ is the solid-angle element, $\mathbf{r}_{jl} = \mathbf{r}_j - \mathbf{r}_l$, k_B is Boltzmann's constant, T is the temperature,

$$\cos\theta_1 = [1 + (T_2\Delta\omega)^2 + \omega_r^2 T_1 T_2]^{-1}[1 + (T_2\Delta\omega)^2],$$
$$\sin\theta_2 = [1 + (T_2\Delta\omega)^2 + \omega_r^2 T_1 T_2]^{-1}[\,|\omega_r| T_2^2\Delta\omega]; \qquad (4)$$

$$\Delta\omega = \omega_0 - |\omega_g|, \; |\omega_g| = |\omega_1 \pm \omega_2|,$$

ω_g is the frequency of the generated gravitons,

$$\hbar\omega_r = |\langle 1|\mathcal{H}_r^j|2\rangle|, \; \mathcal{H}_r = \sum_j \mathcal{H}_r^j,$$

$I_0(\mathbf{k}_g)$ is calculated from the formula[3]:

$$I_0(k_g) = \frac{k_1\omega_g^6}{4\pi c^5}\Big[\frac{1}{4}\Big|\sum_{\mu,\delta}\langle 1|D_{\mu\delta}^m|2\rangle n_\mu n_\delta\Big|^2 + \frac{1}{2}\sum_{\mu,\delta}|\langle|D_{\mu\delta}^m|2\rangle|^2$$
$$- \frac{1}{2}\sum_{\mu,\delta,\varkappa}[\langle 1|D_{\mu\delta}^m|2\rangle\langle 2|D_{\mu\varkappa}^m|1\rangle + \langle 2|D_{\mu\delta}^m|1\rangle\langle 1|D_{\mu\varkappa}^m|2\rangle] n_\delta n_\varkappa\Big], \qquad (5)$$

$$D_{xx}^m = \sqrt{1/6}(D_2^m + D_{-2}^m) - 1/3 D_0^m, \quad D_{zz}^m = 2/3 D_0^m,$$
$$D_{yy}^m = -\sqrt{1/6}(D_2^m + D_{-2}^m) - 1/3 D_0^m,$$
$$D_{xy}^m = D_{yx}^m = -i\sqrt{1/6}(D_2^m - D_{-2}^m),$$
$$D_{yz}^m = D_{zy}^m = i\sqrt{1/6}(D_1^m + D_{-1}^m), \quad D_{xz}^m = D_{zx}^m = \sqrt{1/6}(D_{-1}^m - D_1^m),$$
$$D_{\pm 2}^m = \frac{\sqrt{6}}{4}\alpha_0(L_\pm^j)^2, \quad D_{\pm 1}^m = \frac{\sqrt{6}}{4}\alpha_0(L_z^j L_\pm^j + L_\pm^j L_z^j),$$
$$D_0^m = 1/2\,\alpha_0[3(L_z^j)^2 - L^j(L^j + 1)], \quad \alpha_0 = m_0 Q_0[L^j(2L^j - 1)]^{-1},$$
$$m_0 Q_0 = \Big\langle L^j L^j \Big| \int \rho_g[3(z')^2 - (r')^2]\,dV' \Big| L^j L^j \Big\rangle, \quad L_\pm^j = L_x^j \pm i L_y^j,$$

where k_1 is the gravitational constant; c is the speed of light, $\mu, \delta, \kappa = x, y, z$; n_μ are the direction cosines of the vector $\mathbf{k}_g$, L_ξ^j are the components of the effective orbital motion of the particle j, m_0 is the electron mass; ρ_g is the density of the electron mass at the point with coordinates x′, y′, z′ of the electron shell of the particle j; $dV' = dx'dy'dz'$.

m_0 should be taken to mean the mass of the nuclei if the generator operates at rotational or vibrational levels of molecules, and the mass of the nucleons if it operates at nuclear levels.

In Eq. (3), the coherent part of the gravitational radiation describes the factor containing

$$\sum_{j\neq l}\exp[i[\mathbf{k}_g - (\mathbf{k}_1 + \mathbf{k}_2)]\mathbf{r}_{jl}].$$

This function has a sharp maximum in the direction of $\mathbf{k}_g = \mathbf{k}_1 + \mathbf{k}_2$. As seen from (3), to obtain the maximum possible $I(\omega_g)$ it is necessary that this direction coincide with one of the maxima of $I_0(\mathbf{k}_g)$. In crystals, this can always be done by suitably orienting the sample with respect to $\mathbf{k}_1 + \mathbf{k}_2$. In the case of liquids, gases, and glasses, it is necessary to take into account in the calculation of $I(\omega_g)$ the random orientation of the particles relative to the wave vectors of the exciting generators. For simplicity we confine ourselves to the case of crystalline samples. Assuming the area of the face perpendicular to $\mathbf{k}_1 + \mathbf{k}_2 = \mathbf{n}_0|\mathbf{k}_1 + \mathbf{k}_2|$ to be equal to 4S, $(S/\lambda_g l_0) \gg 1$ (l_0—length of sample, λ_g—wavelength of the generated gravitons, and $\mathbf{n}_0$ coincides with one of the maxima of $I(\mathbf{k}_g)$), and using the results of[11], we find from (3) that the power of the coherent part of the SGI is described by

$$I_{coh}(\omega_g) = I_0(\mathbf{n}_0 k_g)\frac{\lambda_g^2 N^2}{4S}\sin^2\theta_2 \operatorname{th}^2\frac{\hbar\omega_g}{2k_B T}. \qquad (6)$$

This part of SGI can be naturally called henceforth the gravitational ray (GR). The need for satisfying the condition $\mathbf{k}_g = \mathbf{k}_1 + \mathbf{k}_2$ and simultaneously satisfying the laws of energy conservation imposes definite limitations on ω_1, ω_2, $\mathbf{k}_1$, and $\mathbf{k}_2$. Thus, for example, if $\mathbf{k}_1 = \mathbf{n}_0|\mathbf{k}_1|$, and $\mathbf{k}_2 = -\mathbf{n}_0|\mathbf{k}_2|$, then

$$\omega_1 = \frac{\omega_g}{2n}(n + 1), \quad \omega_2 = \frac{\omega_g}{2n}(n - 1).$$

The influence of the intensities of the external generators on $I_{coh}(\omega_g)$ is described by the factor $\sin^2\theta_2$, which reaches its maximum value when the condition $\Delta\omega = T_2^{-1}[1 + \omega_r^2 T_1 T_2]^{1/2}$ is satisfied, and this value equals

$$(\sin\theta_2)_{max} = |\omega_r| T_2[1 + \omega_r^2 T_1 T_2]^{-1/2}. \qquad (7)$$

If the generator power is such that $|\omega_r| \gg (T_1 T_2)^{-1/2}$, then $\sin\theta_2$ reaches a value

$$(\sin\theta_2)_{max\,max} = (T_2/T_1)^{1/2}. \qquad (8)$$

When the transition $|1\rangle \to |2\rangle$ is realized as a result of absorption of two quanta, $\hbar\omega_1 + \hbar\omega_2 = \hbar\omega_e$, then it can be readily shown that

$$|\hbar\omega_r| = \Big|\sum_\alpha \frac{\langle 2|\mathcal{H}_1^j|\alpha\rangle\langle\alpha|\mathcal{H}_2^j|1\rangle}{\hbar[(\omega_\alpha - \omega_2) + i\Gamma_\alpha]} + \frac{\langle 2|\mathcal{H}_2^j|\alpha\rangle\langle\alpha|\mathcal{H}_1^j|1\rangle}{\hbar[(\omega_\alpha - \omega_1) + i\Gamma_\alpha]}\Big|; \qquad (9)$$

$\mathcal{H}_1$ and $\mathcal{H}_2$ are respectively the Hamiltonians of the interaction of the first and second electromagnetic generators with the impurity j, and Γ_α is the width of the level α.

If the transition $|1\rangle \to |2\rangle$ is a result of absorption of a quantum $\hbar\omega_1$ and creation of a quantum $\hbar\omega_2$ ($\omega_g = \omega_1 - \omega_2$), then

$$|\hbar\omega_r| = \Big|\sum_\alpha \frac{\langle 1|\mathcal{H}_1^j|\alpha\rangle\langle\alpha|\mathcal{H}_2^j|2\rangle}{\hbar[(\omega_\alpha + \omega_2) + i\Gamma_\alpha]} + \frac{\langle 2|\mathcal{H}_2^j|\alpha\rangle\langle\alpha|\mathcal{H}_1^j|1\rangle}{\hbar[(\omega_\alpha - \omega_1) + i\Gamma_\alpha]}\Big|. \qquad (10)$$

In the latter case, the vector $\mathbf{n}_0$ divides the angle between $\mathbf{k}_1$ and $\mathbf{k}_2$ (at certain values of ω_g and ω_1) in the ratio $\sin\tilde{\alpha}/\sin\beta = (\omega_1 - \omega_g)/\omega_1$; $\tilde{\alpha}$ is the angle between $\mathbf{n}_0$ and the vector $\mathbf{k}_1$; β is the angle between $\mathbf{n}_0$ and $\mathbf{k}_2$ ($\mathbf{k}_1$, $\mathbf{k}_2$, and $\mathbf{n}_0$ lie in the same plane). In this case

$$\beta = \arccos\Big[\frac{\omega_g}{2(\omega_1 - \omega_g)} + \frac{n}{2\omega_g}(\omega_1 + \omega_g)\Big],$$

$$\omega_2 = \omega_1 \operatorname{tg} \tilde{\alpha}, \quad \tilde{\alpha} = \arcsin [(\omega_1 - \omega_r)\omega_1^{-1} \sin \beta].$$

If the GR is excited by a system with an equidistant spectrum and an effective spin $R > 1/2$, calculations with the aid of (2) lead to the following formula for the intensity of its coherent part

$$I_{cho}(\omega_g) = 4I_0(n_0 k_g)\frac{\lambda_g^2}{9}[R^2(R+1)^2]\frac{N^2}{S}\sin^2\theta_2 \operatorname{th}^2\frac{\hbar\omega_g}{2k_B T}, \qquad (11)$$

from which we get (6) when $R = 1/2$.

Let us stop in conclusion to discuss the possibility of using Landau levels for the generation of GR. The intensity of the GR is calculated in this case by means of (6), where $\sin^2\theta_2$ should be taken to mean the quantity

$$f^2 = \left[\frac{P_0 E}{2\pi\hbar} T_2^2 \Delta\omega\right]^2 \left[1 + (T_2\Delta\omega)^2 + \left(\frac{P_0 E}{2\pi\hbar}\right)^2 T_2^2\right]^{-2},$$

$$P_0 = (4\pi\hbar c e / H_z)^{1/2},$$

where e is the electron charge and H_z is the z component of the constant external magnetic field. The matrix elements of the quadrupole moment between the states whose Landau quantum numbers n_1 differ by unity, are of the order of

$$\frac{2\hbar c}{eH_z}\{(n_1+1)(n_1+l+1)\}^{1/2}$$

where l is the orbital quantum number and E is the intensity of the alternating electric field.

According to the Brans-Dicke theory[12], the pulsations of the mass density should lead to generation of scalar gravitational waves. For a system of N particles pulsating coherently with frequency ω_g, the intensity of the scalar gravitational field is also calculated from formula (6), where $I_0(n_0 k_g)$ is replaced by the quantity[13]:

$$I_{0g} = \frac{4k_1}{9c^5}\frac{\varkappa|A|^2\omega_g^6}{1+6\varkappa}, \quad k_2 = \frac{k_1(1+4\varkappa)}{1+6\varkappa},$$

$$A = \left\langle 1 \left| \int dV'(r')^2 \rho_g \right| 2 \right\rangle, \qquad (5a)$$

where k_2 is the gravitational constant with allowance for the scalar field. According to the existing theories, κ can be either positive or negative, and $|\kappa| \sim 1$[13,14]. The oscillations of the quantity A can also be excited by lasers through oscillations of the charge density of the electron cloud, of the nuclei in the molecule, or of the nucleons in the nucleus. For example, such oscillations occur when the electric dipole moment processes in a plane in which its components are anisotropic.

3. DETECTION OF GRAVITATIONAL RAY

a) Direct Detection Methods

It is most natural to use for the detection of GR the inverse of the generator circuit. The samples used as detectors are perfectly analogous to those used for generation. The gravitational ray, causing a precession of the mass quadrupoles of the impurity particles, causes simultaneously precession of the electric multipoles, with the same frequency, and consequently leads to generation of photons that are registered by ordinary means. Such an experimental setup, naturally, is suitable only for substances with n = 1. In other cases, the experimental setups must be more complicated, by virtue of the fact that the wave vector of the graviton is shorter by a factor of n in such substances than the wave vector of the photon of the same frequency. In such cases it is convenient to carry out the reception in a two-, three-, etc. quantum regime. One of the external generators in this case is the GR. The experimental geometry should be such as to satisfy, together with the energy conservation law, the equality $\mathbf{k}_g + \mathbf{k}_{aux} = \mathbf{k}_{0e}$ ($\mathbf{k}_{aux}$ is the effective wave vector of the auxiliary generator, $|\mathbf{k}_{0e}| = n\omega_0/c$), and the direction of $\mathbf{k}_{0e}$ coincides with one of the spontaneous electrodipole or electroquadrupole radiations $I_0(\mathbf{k}_{0e})$ of the particle.

For example, one can use as an external generator a generator of ultrasonic oscillations. The frequency ω_{pn} of such a generator can be determined from the equation

$$\omega_0 - \omega_g = \omega_{pn}, \quad |\mathbf{k}_{aux}| = |\mathbf{k}_{pn}| = \omega_{pn}/v,$$

where v is the speed of sound. Let q_0 be the direction of one of the maxima of $I_0(\mathbf{k}_{0e})$, and α the angle between q_0 and $\mathbf{k}_g$. Then the angle $(-\beta)$, at which it is necessary to generate the sound (with respect to q_0), is determined from the condition

$$\cos\beta = \frac{c(\omega_0 - \omega_g)}{2nv\omega_0}, \quad \cos\alpha = -\frac{c^2(\omega_0-\omega_g)^2}{2nv^2\omega_0\omega_g}, \qquad (12)$$

and the intensity of the coherent part of the electromagnetic radiation generated in this case, $I_{coh}(\omega_{0e})$, is calculated from a formula similar to (5):

$$I_{cho}(\omega_{0e}) = I_0(k_{0e}q_0)\frac{\lambda_{0e}^2 N^2}{4S}\sin^2\theta_{ge} \operatorname{th}^2\frac{\hbar\omega_{0e}}{2k_B T}, \qquad (13)$$

where λ_{0e} is the wavelength of the electromagnetic radiation, corresponding to the frequency ω_{0e} in the medium; $\sin\theta_{ge}$ can be calculated with the aid of formula (7). The quantity ω_r contained in (7) is calculated for this case from formulas (9) and (10) making the substitutions $\mathcal{H}_1^j \to \mathcal{H}_{gQ}^j$, $\mathcal{H} \to \mathcal{H}_{ip}^j$, $\omega_1 \to \omega_g$, and $\omega_2 \to \omega_{pn}$; $\mathcal{H}_{gQ}^j$ is the Hamiltonian of interaction of the gravitational ray with the impurity j; $\mathcal{H}_{ip}^j$ is the Hamiltonian of the ion-phonon interaction; the operator $\mathcal{H}_{gQ}$ is written here in the form of a contraction of spherical tensor operators of second rank at $R > 1/2$[1]:

$$\mathcal{H}_{gQ}^j = \sum_{p=-2}^{2} (-1)^p T_{2p}^j(\Gamma) T_{2(-p)}^j(R)\delta_{2|p|},$$

$$T_{2\pm2}^j(\Gamma) = t_{2\pm2}^j(\Gamma) m_0 Q_0 c^2 R_{0x0}^{\mu};$$

$$t_{2\pm2}^j(\Gamma) = (3/2)^{1/2}[d_2 R^j(2R^j-1)]^{-1},$$

$$R_{0x0} = \omega_g[k_1 I_{cho}(\omega_g)/\pi c^7 S]^{1/2},$$

$$d_2 = 2(5)^{1/2}[(2R^j+3)(2R^j+2)(2R^j+1)2R^j(2R^j-1)]^{-1/2},$$

$$T_{2\pm2}^j(R) = (3/2)^{1/2} d_2 R_{\pm}^{j2},$$

$$R_{\pm}^j = R_x^j \pm iR_y^j. \qquad (14)$$

$R_{0x_0}^{\mu}$ is the component of the Riemann curvature tensor[10], and $\delta_{2|p|}$ is the Kronecker symbol.

We write the expression for $\mathcal{H}_{ip}^j$ in the form

$$\mathcal{H}_{ip}^j = \sum_{\eta\zeta s_1 t} G_{\eta\zeta s_1 t} R_\eta^j R_\zeta^j u_{s_1 t}^0, \qquad (15)$$

where $G_{\eta\zeta s_1 t}$ is the tensor of the ion-phonon interactions, characterizing the coupling between the impurity and the lattice, and $u^0_{s,t}$ is the amplitude of the deformation tensor. For example, if the photon is produced as a result of absorption of a phonon and a graviton, then

$$\hbar^2\omega_r^{ge} = m_0 Q_0 c^2 \omega_g [k_1 I_{cho}(\omega_g) / \pi c^7 S]^{1/2} \times \Big| \sum_{\xi,\, p;\, \eta\zeta s_1 t} t^j_{2(p)}(\Gamma) G_{\eta\zeta s_1 t} u_{s_1 t}{}^0 \delta_{2|p|}$$
$$\times \Big[\frac{\langle 2|T^j_{2(-p)}(R)|\xi\rangle\langle\xi|R_\eta{}^j R_\zeta{}^j|1\rangle}{(\omega_\xi - \omega_{pn}) + i\Gamma_\xi} + \frac{\langle 2|R_\eta{}^j R_\zeta{}^j|\xi\rangle\langle\xi|T^j_{2(-p)}|1\rangle}{(\omega_\xi - \omega_r) + i\Gamma_\xi} \Big]\Big| \quad (16)$$

where $|\xi\rangle$ is the intermediate state. We can use, instead of the ultrasonic pumping, two laser beams with frequencies ω_{1p} and ω_{2p}, and with wave vectors $\mathbf{k}_{1p}$ and $\mathbf{k}_{2p}$ such that the resultant wave vector satisfies the conditions $\mathbf{k}_e = \mathbf{k}_{ep} + \mathbf{k}_g$ and $\mathbf{k}_{ep} = \mathbf{k}_{1p} + \mathbf{k}_{2p}$. If the production of the quantum $\hbar\omega_e$ is the result of the absorption of the quanta $\hbar\omega_g$, $\hbar\omega_{1p}$, and $\hbar\omega_{2p}$, then ω_r^{ge} can be estimated from the equation

$$\omega_r^{ge} \sim \hbar^{-3} m_0 Q_0 c^2 \omega_g [k_1 I_{cho}(\omega_g) / \pi c^7 S]^{1/2} E_{1\pi} E_{2\pi}$$
$$\times \Big| \sum_{p,\xi,\Phi} t^j_{2(p)}(\Gamma)\delta_{2|p|} \frac{\langle 2|T_{2(-p)}(R)|\xi\rangle\langle\xi|\mathbf{i}_{1\pi}\mathbf{P}^j|\Phi\rangle\langle\Phi|\mathbf{i}_{2\pi}\mathbf{P}^j|1\rangle}{(\omega_\Phi - \omega_{2\pi} + i\Gamma_\Phi)(\omega_\xi - \omega_{1\pi} + i\Gamma_\xi)} \Big| \quad (17)$$

where $|\Phi\rangle$ is the intermediate state, E_{1p} and E_{2p} are the field intensities of the auxiliary generators, $\mathbf{i}_{1p}$ and $\mathbf{i}_{2p}$ are their polarizations, $\mathbf{P}^j$ is the operator of the dipole moment of the particle j, while the angle α_1 between $\mathbf{q}_0$ and $\mathbf{k}_g$ and the angle $-\beta_1$ between $\mathbf{q}_0$ and the geometric sum $\mathbf{k}_{1p} + \mathbf{k}_{2p}$ should satisfy the condition

$$\cos\alpha_1 = \frac{n^2(\omega_e^2 - \omega_4^2) + \omega_g^2}{2n\omega_g\omega_e}, \qquad \cos\beta_1 = \frac{n^2(\omega_e^2 + \omega_4^2) - \omega_g^2}{2n^2\omega_e\omega_4},$$
$$\omega_4 = (\omega_{1\pi}^2 + \omega_{2\pi}^2 - 2\omega_{1\pi}\omega_{2\pi}\cos\alpha_2)^{1/2}, \quad (18)$$

α_2 is the angle between $\mathbf{k}_{1p}$ and $\mathbf{k}_{2p}$.

To estimate the order of magnitude of $I_{coh}(\omega_e)$, let us estimate ω_r^{ge}. In view of the small values of $I_{coh}(\omega_g)$ obtained in the preceding section, we can put in formula (3) $\omega_r^2 T_1 T_2 \ll 1$, which yields

$$\text{a)}\ T_2\Delta\omega \gg 1, \qquad \sin\theta_{ge} = |\omega_r^{ge}|\Delta\omega^{-1},$$
$$\text{b)}\ T_2\Delta\omega \ll 1, \qquad \sin\theta_{ge} = |\omega_r^{ge}|T_2^2\Delta\omega. \quad (19)$$

It must be emphasized that in the two-quantum reception method the gravitational ray serves, as it were, as a means of controlling the frequency and the direction of the electromagnetic radiation. The energy of this electromagnetic radiation, on the other hand, is drawn naturally from the energy of the laser beam.

b) Indirect Methods of Detecting a Gravitational Ray

Let us consider the following process: N impurities in a solid matrix are illuminated by a powerful laser beam. Obviously, it is perfectly feasible to have a process in which one quantum of electromagnetic radiation $\hbar\omega_e$ is absorbed and a gravitational quantum $\hbar\omega_g$ (as a result of the interaction of the impurities with the zero-point oscillations of the gravitational field) and a quantum of acoustic oscillations $\hbar\omega_{pn}$ are emitted. The situation here is the inverse of that discussed in subsection a. Consequently, for the detection of gravitational waves, there is no need in a generation-reception double conversion. They can be identified by observing the sound generated as a result of the scattering of the photons (phonon-gravitational scattering). The dependence of the frequency of the sound generated in such a scattering on the angle θ between the direction of the wave vector of the sound and the direction of the laser beam is given by

$$\omega_{pn} = \frac{v}{c}\omega_{0e}[n\cos\theta \pm \sqrt{1 - n^2\sin^2\theta}]. \quad (20)$$

It is possible to consider with perfect analogy the case when a quantum of electromagnetic radiation $\hbar\omega_{sc}$ and a graviton $\hbar\omega_g$ are created as a result of absorption of the quanta $\hbar\omega_{1p}$ and $\hbar\omega_{2p}$ (photon-graviton scattering). The dependence of the frequency of the scattered light ω_{sc} on ω_{1p}, ω_{2p}, and on the angle θ_1 between the direction of the geometrical sum $\mathbf{k}_{1p} + \mathbf{k}_{2p}$ and the direction of observation is given by

$$\omega_{sc} = (n^2 - 1)^{-1}\{(n^2\omega_4\cos\theta_1 - \omega_5) + [(n^2\omega_4\cos\theta_1 - \omega_5)^2 + (n^2 - 1)(\omega_5^2 - n^2\omega_4^2)]^{1/2}\}, \quad \omega_5 = \omega_{1\pi} + \omega_{2\pi}. \quad (21)$$

To calculate the intensity of the sound and light generated in this case it is necessary to use formulas similar to (6) and (13). Inasmuch as the absorption occurs in this case in the single-quantum mode, we can always put $\sin^2\theta_2 \sim 1$. But $I_0(\mathbf{k}_{pn})$ or $I_0(\mathbf{k}_{sc})$ must in this case be taken to mean the intensity of the spontaneous decay of the isolated particle with simultaneous creation of a phonon and graviton or a photon and graviton under the influence of the zero-point oscillations of the phonon and graviton or photon and graviton fields.

In phonon-graviton scattering we have

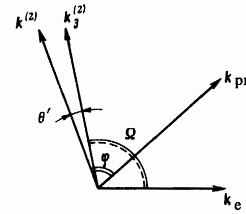
$$I_0(\mathbf{k}_{pn}) = \frac{k_1 m_0^2 n^4 \omega_{pn}^4 \Delta\omega_{pn}\omega_0^5}{2\hbar(2\pi)^4\rho v^5 c^5} \Big| \sum_{\eta\zeta s_1 t\alpha} G_{\eta\zeta s_1 t} d_{s_1 t}$$
$$\times \Big[\frac{\langle 2|Q_0{}^j|\alpha\rangle\langle\alpha|R_\eta{}^j R_\zeta{}^j|1\rangle}{\omega_\alpha + \omega_{pn}} + \frac{\langle 2|R_\eta{}^j R_\zeta{}^j|\alpha\rangle\langle\alpha|Q_0{}^j|1\rangle}{\omega_\alpha + \omega_e} \Big]\Big|^2_{av}, \quad (22)$$

$d_{s,t} = (1/2)(l^0_{s_1}k^0_t + k^0_{s_1}l^0_t)$; $l^0_{s_1}$ and k^0_t are respectively the s_1 and t components of the unit vector of polarization of the generated phonons and of the unit wave vector ($\mathbf{k}^0 = \mathbf{k}_{pn}/|\mathbf{k}_{pn}|$), $d_{s_1 t}$ is a quantity of the order of unity, and av denotes averaging over the direction of $\mathbf{k}^0$.

In photon-graviton scattering we have

$$I_0(k_{pt}) = \frac{\beta^2(\theta_0)[1 - \beta(\theta_0)]^5\omega_0^7\Delta\omega_{pt}k_1 m_0^2}{(2\pi)^3\hbar c^8}$$
$$\times \Big| \sum_\alpha \Big[\frac{\langle 2|Q_0{}^j|\alpha\rangle\langle\alpha|\mathbf{i}\mathbf{P}^j|1\rangle}{\alpha(\omega_0) + 1} + \frac{\langle 2|\mathbf{i}\mathbf{P}^j|\alpha\rangle\langle\alpha|Q_0{}^j|1\rangle}{\alpha(\omega_0) + [1 - \beta(\theta_0)]} \Big]\Big|^2,$$
$$\alpha(\omega_0) = \omega_\alpha/\omega_0, \qquad \beta(\theta_0) = \omega_{pt}/\omega_0. \quad (23)$$

Unfortunately, during the first stage, indirect methods of graviton-field detection that are convenient from the experimental point of view yield, as shown by estimates, an unobservable power of the phonon or photon fields. It is possible that photon-graviton scattering may become observable if the phonons created during the first stage of the phonon-graviton scattering are used again for excitation in a two-quantum regime (the phonon field created as a result of phonon-graviton scattering plus a laser beam of frequency $\omega^{(2)}$) of a photon Bloch induction between $|1\rangle$ and some level $|3\rangle$ such that $\omega_3 \approx \omega_{pn} + \omega^{(2)}$. The experimental scheme is as follows: a laser beam of frequency $\omega_e \approx \omega_2$ is incident on a sample with impurities having three discrete levels $E_1 < E_3 < E_2$. As a result of the phonon-graviton scattering, a phonon coherent field of intensity $I_{coh}(\omega_{pn})$ is produced. This phonon field, together with the field of a second laser of frequency $\omega^{(2)}$, intensity $E^{(2)}$, and wave vector $\mathbf{k}^{(2)}$ ($\omega^{(2)} + \omega_{pn} \approx \omega_3$), excites a photon Bloch induction at the transition $|1\rangle \to |3\rangle$, with emission of a coherent photon field of frequency $\omega_e^{(2)} = \omega_3$, which is recorded by the usual method. The figure shows the experimental scheme.



Scheme of experiment for indirect detection of gravitational waves in phonon-graviton scattering (second stage).

Using (21) and the connection between the frequencies ω_{pn}, $\omega^{(2)}$ and the angle φ,

$$\omega_{pn} = 2n\omega^{(2)}\frac{v}{c}\cos\varphi, \tag{24}$$

we find that ω_e, $\omega^{(2)}$, $\omega_e^{(2)}$, θ', Ω and n are connected in this case by the following relation:

$$\sin\Omega = \cos\theta'\Big\{\Big(\frac{\alpha'}{2}\sin\theta' + \frac{n^2-1}{4n^2}\operatorname{ctg}\frac{\theta'}{2}\Big) + \Big(\sin^2\frac{\theta'}{2} - \Big[\alpha'\sin\frac{\theta'}{2} + \frac{n^2-1}{4n^2}\Big]^2\Big)^{1/2}\Big\} - \sin\theta'\Big\{\Big(\alpha'\sin^2\frac{\theta'}{2} + \frac{n^2-1}{4n^2}\Big) + \Big(\cos^2\frac{\theta'}{2} - \Big[\frac{\alpha'}{2}\sin\theta' + \frac{n^2-1}{4n^2}\operatorname{ctg}\frac{\theta'}{2}\Big]^2\Big)^{1/2}\Big\},$$
$$\alpha' = \omega^{(2)}/\omega_e, \tag{25}$$

which yields for $\theta' = \pi/2$

$$\sin\Omega = -\Big\{\Big(\frac{\alpha'}{2} + \frac{n^2-1}{4n^2}\Big) + \Big[\frac{1}{2} - \Big(\frac{\alpha'}{2} + \frac{n^2-1}{4n^2}\Big)^2\Big]^{1/2}\Big\}. \tag{26}$$

The intensity of the photons $\mathbf{k}_e^{(2)}$ generated as a result of two-quantum absorption of photons $\omega^{(2)}$ and phonons ω_{pn} is calculated by means of a formula similar to (5):

$$I_{cho}(\omega_e^{(2)}) = I_0(k_e^{(2)})\frac{\lambda_{23}^2 N^2}{2S}\sin^2\theta_e^{(2)}\operatorname{th}^2(h\omega_3/2k_B T), \tag{27}$$

$$\sin\theta_e^{(2)} = \begin{cases} |\omega_r^{(2)}|\,\Delta\omega_{(2)}^{-1}, & T_2\Delta\omega_{(2)} \gg 1, \\ |\omega_r^{(2)}|\,T_2^2\Delta\omega_{(2)}, & T_2\Delta\omega_{(2)} \ll 1; \end{cases}$$

$$|\omega_r^{(2)}| = \hbar^{-2}E_{(2)}^2\Big|\sum_{\alpha\eta s_1\zeta t} G_{\eta\zeta s_1 t}\, d_{s_1 t}[16 I_{cho}(\omega_{pn})(\rho v^3 S)^{-1}]^{1/2} \times \frac{\langle 3|R_\eta^j R_\zeta^j|\alpha\rangle\langle\alpha|\mathbf{i}^{(2)}\mathbf{P}^j|1\rangle}{\omega_\alpha - \omega_{pn}} + \frac{\langle 3|\mathbf{i}^{(2)}\mathbf{P}^j|\alpha\rangle\langle\alpha|R_\eta^j R_\zeta^j|1\rangle}{\omega_\alpha - \omega^{(2)}}\Big|^2, \tag{28}$$

ρ is the sample density, $\mathrm{i}^{(2)}$ is the polarization vector of the laser beam $\omega^{(2)}$, and $E_{(2)}$ is the intensity of its electric field. In photon-graviton and phonon-graviton scattering, stimulated scattering processes are possible in principle. To this end, naturally, it is necessary to suppress the Mandel'shtam-Brillouin scattering channels.

c) Reception of Gravitational Ray in the Boson Cascade Regime

As shown earlier[15], when negative populations are produced in a system of impurity centers (we refer to such a system as an inverted system), cascade-like development of superradiant states, accompanied by powerful coherent radiation, are possible in such a system. Such a process is initiated either by a photon produced during spontaneous decay of the system itself, or by a small coherent external disturbance. In our case such a disturbance is the GR. For the same reason that the generation of GR is more effective in the two-quantum regime, the reception of GR by inverted systems is also more conveniently realized with additional laser illumination. The frequency ω_5 in the direction of the wave vector $\mathbf{k}_5$ in the laser illumination should be chosen such that $\omega_5 \pm \omega_g = \omega_0$, and $\mathbf{k}_5 + \mathbf{k}_g$ corresponds to the wave vector of the electromagnetic radiation of frequency ω_0, while the direction of $\mathbf{k}_5 + \mathbf{k}_g$ coincides with one of the maxima of the spontaneous electromagnetic radiation (dipole or quadrupole) of the isolated particle $I_0(\omega_{0e})$. When these conditions are satisfied, the intensity of the photon avalanche due to the joint action of the GR and the laser illumination reaches its maximum value within a time

$$t_1 = \Big(\ln\operatorname{ctg}\frac{\varphi_1}{2}\Big)\frac{\hbar\omega_0 S}{I_0(\omega_{0e})N\lambda_{0e}^2}, \tag{29}$$

where S is the area of the phase perpendicular to $\mathbf{k}_5 + \mathbf{k}_g$, and φ_1 is given by the formula

$$\varphi_1 = \tau\hbar^{-1}E_5\Big|\sum_\alpha \frac{\langle 2|\mathbf{i}_5\mathbf{P}^j|\alpha\rangle\langle\alpha|\mathscr{H}_{gQ}^j|1\rangle}{\hbar[(\omega_\alpha + \omega_g) + i\Gamma_\alpha]} + \frac{\langle 2|\mathscr{H}_{gQ}^j|\alpha\rangle\langle\alpha|\mathbf{i}_5\mathbf{P}^j|1\rangle}{\hbar[(\omega_\alpha - \omega_1) + i\Gamma_\alpha]}\Big|, \tag{30}$$

where E_5 is the field intensity, τ the duration of the laser-illumination pulse, and $\mathbf{i}_5 E_5 = \mathbf{E}_5$.

In view of the weakness of the GR in (29), φ_1 can be regarded as a quantity much smaller than unity. We then get from (29)

$$t_1 = \ln\Big(\frac{2}{\varphi_1}\Big)\frac{\hbar\omega_{0e}S}{I_0(\omega_{0e})N\lambda_{0e}^2}. \tag{31}$$

Let us estimate (25) under the following assumptions:

$$\lambda_{0e} \sim 10^{-5}\ \mathrm{cm},\quad I_0(\omega_{0e}) \sim \hbar\omega_0/\tau_1,$$

τ_1 is the time of spontaneous decay of the isolated particle with creation of a quantum $\hbar\omega_{0e}$, $\tau_1 \sim 10^{-5}$ sec, $N \sim 10^{22}$, $S = 1\ \mathrm{cm}^2$; we estimate φ_1 from (30) at $I_{coh}(\omega_g) \sim 25 \times 10^{-11}$ erg/sec, $\omega_{0e} = 10^{16}\ \mathrm{sec}^{-1}$, $\tau \sim 10^{-8}$ sec; $t_1 \sim 10^{-11}$ sec. It is important here that t_1 be much shorter than T_2^*, to prevent relaxation of the arising coherent states. If the inversion is incomplete, it is necessary to substitute the population difference in (31) in lieu of N.

Obviously, the reception of GR by inverted systems can be effective also in the echo regime. To this end, the system is first excited in a two-quantum regime with an electromagnetic pulse of duration t_2 from two lasers with wave vectors $\mathbf{k}_{1p}$ and $\mathbf{k}_{2p}$ and frequencies $\omega_{1p} + \omega_{2p} = \omega_{0p}$, the power of which ensures in the system of N impurities a margin of energy corresponding to the negative populations ($t_2 \ll T_2^*$), and $|\mathbf{k}_{1p} + \mathbf{k}_{2p}| \neq |\mathbf{k}_{0e}|$ ($|\mathbf{k}_{0e}|$ is the modulus of the wave vector of the photon corresponding to the frequency ω_{0e}), the direction of $\mathbf{k}_{1p} + \mathbf{k}_{2p}$ coincides with one of the minima of the intensity of the spontaneous radiation of the isolated impurity, and this should prevent the spontaneous photon decay.

If now we subject the system at an instant of time $T_2^* < t_3 \ll T_2$ to a second pulsed action of a coherent graviton ray and laser illumination (wave vector k_3, the corresponding frequency is ω_3), in such a way that $|k_g + k_3 - 2(k_{1p} + k_{2p})| = |k_{0e}|$, and the direction of $(k_g + k_3) - 2(k_{1p} + k_{2p})$ coincides with one of the maxima of $I_0(\omega_{0e})$, then at the instant of time $2t_3 < T_2$ the system of impurities will begin to generate a coherent electromagnetic signal of frequency ω_{0e} in the direction $k_g + k_3 - 2(k_{1p} + k_{2p})$ (echo signal). Thus, if $k_{1p} = q_0 n\omega_{1p}/c$, $k_{2p} = -q_0 n\omega_{2p}/c$, $k_3 = q_0 n\omega_3/c$, $k_g = -q_0\omega g/c$, $\omega_g = \omega_{0e} - \omega_3$, and $\omega_{0e} = \omega_{1p} + \omega_{2p}$, then ω_{1p}, ω_{2p}, and ω_3, for given n and ω_g, should satisfy the conditions (T_2 is the time of irreversible phase relaxation)

$$\omega_{1p} = \omega_{0e} - \omega_g(n+1), \quad \omega_{2p} = \omega_g(n+1), \quad \omega_3 = \omega_{0e} - \omega_g. \quad (32)$$

The reception of coherent scalar gravitational rays can be realized in analogy with tensor waves. However, since a scalar wave can change the parameters of the magnetic-resonance spectra[16] etc. via the scalar parameters, it should cause modulation of the frequency of the precessing multipoles. This phenomenon can be used for the reception of scalar waves of cosmic origin.

In a number of recent papers[17-19] it is proposed to improve the schemes for generating GR under laboratory conditions[1]. Weber and Hinds[18] state that in[1], in the calculation of the intensity of the GR generation, we have used without justification the first order of perturbation theory. Actually we have used the formalism of the theory of optical and spin echo, in which we have summed the principal terms of the entire perturbation-theory series. Beall[19] states that our scheme for the excitation of GR will not work, owing to the disparity between the selection rules for the dipole and quadrupole moments, with Beall[19] proposing to get around this difficulty by two-quantum excitation. As already stated in Sec. 1, special selection rules hold true in the pulse excitation regime, and they enable us to obtain the result reported in[1]. The authors of[18] likewise indicate that in[1] we do not take into account the inequality of the wave vectors of the gravitational and light rays, and that this greatly reduces the effectiveness of the proposed scheme, while Sinsky and Weber propose to overcome this obstacle by using nonlinear (two-quantum) excitation. First, we have noted this circumstance in[1], and in[2] we have proposed a two-quantum excitation scheme free of this shortcoming. Westervelt's criticism[17] was answered by us in[2].

4. DISCUSSION OF RESULTS

An analysis of Tables I and II shows that the generation and reception of coherent gravitational rays under laboratory conditions are possible in principle (provided, naturally, such rays exist and their interaction with matter is correctly described by the existing theory of the weak gravitational field[21]). Under the most favorable conditions we can obtain at the receiver output 10^{-2} photons/sec at a frequency $\omega = 10^{16}$ rad/sec. However, besides a coherent electromagnetic signal, noise photons will be generated at the receiver output. Therefore the signal/noise ratio is important.

The noise may differ in nature. First, it contains the incoherent photons whose frequencies and wave-vector directions are identical with those of the coherent-signal photons. If the reception of the signal is effected by a system in the ground state or in Bose-avalanche regime, then the signal/noise ratio is determined respectively by the formulas for $N\lambda_e^2$ or $N\lambda_e^2 \sin^2 \varphi_{max}$, where $\sin(\varphi_{max}/2)$ describes the fraction of the ground state in the superposition state at the instant of time t_1 of maximum development of the boson avalanche (see (29)—(31)). The number $N\lambda_e^2 \sim 10^6$—10^4 is quite large. As to $\sin^2 \varphi_{max}$, it can also reach a value on the order of unity. Second, we can have a noise background at other frequencies or at the signal frequency, but with other wave vectors due to thermal vibrations of the receiver, scattering by defects, nonlinear effects, etc. In principle, the influence of these factors can be greatly reduced by lowering the receiver temperature, by using perfect samples of high chemical purity, and also by using the selective properties of the receiver channel.

However, an actual realization of such experiments entails great experimental difficulties. First, both the generator and the receiver should have a value on the order of one cubic meter, and this requires powerful lasers capable of exciting such volumes of matter. Second, it is necessary to develop further the technique of directional reception of ultraweak coherent signals in the two-quantum regime in the optical range. The weakness of the registered signal is compensated for by the power of the auxiliary pumping which has a different physical nature and frequency, obeys different quantum-mechanical selection rules, and has a different direction of the effective wave vector. One can hope that the use of several stages of such a reception method will lead to a decrease of the value of the GR generator and receiver. Therefore gravitational experiments must be preceded by a preparatory stage in which such reception methods are developed. The latter, obviously, is also of great independent scientific and technical interest.

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