DETECTION OF GRAVITATIONAL WAVES BY THE METHOD OF LIGHT SCATTERING BY ELASTIC OSCILLATIONS

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The scheme of gravitational wave detection which uses the phenomenon of light scattering by the elastic wave these waves cause is discussed when the presence of the gravitational waves can be judged by the presence of fine components of the scattered light spectrum. Estimates carried out show the possibility of an experimental realization of the proposed scheme.

The detection of gravitational waves is one of the fundamental problems in proving the assertions of general relativity theory [1, 2]. Up to now a number of methods of solving this problem has been proposed [1-8].

The scheme of a graviton detector considered herein uses the phenomenon of scattering of photon, neutron, electron, phonon, γ-quanta, etc., radiation by the elastic (phonon) wave caused by the gravitons.

1. Scheme of Detector Operation

A gravitational wave of frequency \( \omega \) evokes an elastic wave of the same frequency \( \omega \) and with the wave vector \( q \) in a crystal [1, 2]. If a monochromatic light ray of frequency \( \omega_0 \) and with the wave vector \( \kappa \) is incident on this crystal at the angle \( \Theta \) determined from the expression

\[
\sin \frac{\Theta}{2} = \frac{\lambda \cdot q}{4 \pi \cdot n},
\]

where \( \lambda \) is the light wavelength, \( q = 2\pi / \Lambda \); \( \Lambda \) is the elastic wavelength, \( n \) is the refractive index, then light scattering should be observed in the directions \( \kappa, \kappa + q \) with the frequencies: \( \omega_0 \) (Rayleigh scattering), \( \omega_0 + \omega \) (Mandel’shtam-Brillouin scattering [9]). The presence of gravitational waves can therefore be judged by the presence of a fine structure in the scattered light spectrum in the absence of other sources of elastic waves.

By using this phenomenon, the gravitational waves can be received according to the following scheme. The gravitational waves radiated by some source will act on two space-diversity "antennas" which are massive aluminum cylinders. Aluminum is selected as the material because of its poor susceptibility to the effect of an electromagnetic field. The acoustic oscillations originating in the "antennas" will be transmitted by lithium niobate (LiNbO\(_3\)) monocrystals glued to one of the endfaces of each of the "antennas." Two lateral, parallel cuts are made parallel to the "antenna" axis on the monocrystals, and a monochromatic light ray is delivered to one of the cuts. The light scattered by the acoustic oscillations in the crystal (caused by the gravitational wave) is determined by photocell sensors. The light frequency should be remote from the frequency band of intrinsic crystal lattice absorption which is in the middle or far infrared ranges of the optical spectrum. The LiNbO\(_3\) is selected as the medium wherein the light will be scattered both because of its high refractive index \( n = 2.2 \) (although there are crystals with greater \( n \) [10]) as well as its good emissivity properties. The LiNbO\(_3\) monocrystal should be carefully shielded from electromagnetic noise. Moreover, each of the detectors ("antenna" plus lithium niobate) should be cooled to low temperatures

\[ T < \hbar \omega / k_B, \]

where $k_B$ is the Boltzmann constant. Thus, $T \sim 0.1^\circ K$ for the frequency $\omega \sim 10^{10}$ sec$^{-1}$.

Two "antennas" are needed in order to perform reception by the "coincidence scheme" realized in practice in [2] to extract a gravitational radiation pulse from the inevitable noise background; only those signals should be taken into account which are determined by both detectors. Each apparatus should be shielded from seismic noise by a series of rubber gaskets [1]. Let us note that the present detection method imposes frequency constraints on the gravitational waves received, namely:

$$\omega \geq \frac{2 \cdot 10^6 \cdot \sin \frac{\Theta}{2} \cdot \nu_0}{c}.$$  (3)

The following are the peculiarities of the method proposed as compared with the methods developed by other authors [1-8]:

1) The scattered light whose quantum energy $\hbar \omega_0$ is approximately $10^5$-$10^6$-fold greater than the quantum energy of gravitational radiation $\hbar \omega$ is to be recorded in the case under consideration;

2) If the source of the incident ray is a laser, then the scattered light is also coherent and can later be amplified by quantum amplifiers, which will also raise (10$^5$-fold and more) the sensitivity of the proposed method of receiving gravitational waves.

2. Dependence of the Intensity of the Scattered Light

Fine Structure Component on the Intensity of the Gravitational Radiation Incident on the Detector

As is known (see [1], for example), a gravitational wave receiver is a receiver of quadrupole type, i.e., should have, as a minimum, two test masses $m$ whose relative motion is caused by the gradient of an elastic wave produced by gravitons. Let the spacing between these masses be $l$, and the displacement of each relative to the other let be $\xi$. Then, as follows from the general theory of relativity [1, 2], the components $\xi^\mu$ of the displacement caused by a gravitational wave are subject to the following equation:

$$\frac{d^2 \xi^\mu}{dt^2} + \frac{D_{\alpha}}{m} \frac{d \xi^\alpha}{dt} + \frac{K^\mu}{m} \xi^\alpha = -c^2 \cdot R_{\alpha (\xi)} \cdot l^\alpha,$$  (4)

where $D^\mu_{\alpha}$ and $K^\mu_{\alpha}$ are tensor components defining the elastic properties of the specimen (the former defines wave damping, and the latter the amplitude of the quasi-elastic force), $R_{\alpha (\xi)}$ are the Riemann curvature tensors, $t$ is the time, and $c$ the velocity of light.

When using the weak field approximation in the case of receiving a sinusoidal gravitational wave, the solution of (4) is

$$\xi^\mu(t) = \frac{m c^2 \cdot R^\alpha_{\alpha (\xi)} (\omega) \cdot l^\alpha}{\omega^2 m - i \omega \cdot \cdot D_{\alpha} \cdot \xi^\alpha - K \xi^\alpha},$$  (5)

where $\delta^\mu_{\alpha}$ is the Kronecker symbol, and the tensors $D^\mu_{\alpha}$, $K^\mu_{\alpha}$ are assumed to have one of the components $D^1_{\alpha} = D$ and $K^1_{\alpha} = K$. The power of the elastic waves in the crystal, caused by the gravitational waves, can be evaluated by means of the formula [2]

$$P_{\alpha \beta} = \frac{15 \pi \cdot G \cdot l^2 \cdot m \cdot (\omega^2 c^2 - Q)}{8 \omega \cdot c} l^\alpha l^\beta,$$  (6)

where $G$ is the gravitational constant $6.67 \cdot 10^{-8}$ cm$^3$ g$^{-1}$ sec$^{-2}$, $Q = (\omega \cdot m) \Delta m$; $\Delta m$ is the damping associated with internal irreversible processes, $T_{g}$ is the flux of gravitational radiation intensity at the location of the test masses

$$T_{g} \approx \frac{c^2 \cdot (F^\mu_{\text{Gr}})^2}{8 \pi \cdot G \cdot m^2 \cdot l^2 \cdot \omega^2},$$  (7)

$F^\mu_{\text{Gr}}$ is the difference between forces acting on the two test masses $m$ of the gravitational wave generator, $l$ is the spacing between between the test masses of the generator. In order to extract the signal caused by the gravitational wave from the fluctuating force background, it is necessary that

$$F^\mu_{\text{Gr}} \gg \sqrt{P_{F / \text{Fl}}},$$

where $F_{F / \text{Fl}}$ is the sum of all fluctuating forces acting on the test masses, and under equilibrium thermal