$$f(\rho)=(\rho^2+\lambda)\varphi_1, \qquad \varphi_1=\ln[(\rho^2+\lambda)/\rho_c^2],$$
$$f_\rho=2\rho(\varphi_1+1), \qquad f_{\rho\rho}=2(\varphi_1+3)-4\lambda/(\rho^2+\lambda). \tag{II.1}$$

By virtue of the inequality (17), the second term in $f_{\rho\rho}$ can be ignored. Indeed, in the case $\rho^2 \gg \lambda$ it is small. For $\rho^2 \lesssim \lambda$, this term is of order unity, but then by virtue of $\lambda \ll \rho_c^2$, $|\varphi_1| \gg 1$ determines the value of $f_{\rho\rho}$. Substitution of (II.1) in (14) gives

$$y+\left\{2(\varphi_1+1)\left[\frac{3y'}{r^3}+\frac{K}{r^6(1+f_\rho)^2}\right]\left(\frac{ry'}{2}-y\right)\right.$$
$$-\frac{r^4}{6}\left[\frac{3y'}{r^3}+\frac{K}{r^6(1+f_\rho)^2}\right]^2\varphi_1+2ry(\varphi_1+3)$$
$$\left.\times\left[-\frac{3y''}{r^3}+\frac{9y'}{r^4}+\frac{6K}{r^7(1+f_\rho)^2}\right]\left[1-\frac{2Kf_{\rho\rho}}{r^6(1+f_\rho)^3}\right]^{-1}\right\}=E+\frac{K(1+2f_\rho)}{6r^2(1+f_\rho)^2}. \tag{II.2}$$

If

$$|\rho_{max}| \ll \varphi_1^{-1}(\rho_{max}), \quad K/r_{min}^6 \ll |\rho_{max}| \tag{II.3}$$

then from (II.2) and (II.1) we have

$$y+\left\{6(\varphi_1+1)\frac{y'}{r^3}\left(\frac{ry'}{2}-y\right)-\frac{3}{2}\frac{(y')^2}{r^2}\varphi_1\right.$$
$$\left.-ry(\varphi_1+3)\left(\frac{6y''}{r^3}-\frac{18y'}{r^4}\right)\right\}=E+\frac{K}{6r^2}+O(r^{-5}). \tag{II.4}$$

Hence, after regrouping and introduction of ρ_* instead of ρ_c we obtain (21).

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The Cavendish experiment at large distances

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The ratio of the gravitational constants G is measured for masses interacting at distances r_1 and r_0 or r_2 and r_0 ($r_0 \approx 0.4$ m, $r_1 \approx 0.3$ m, $r_2 \approx 10$ m) for the purpose of verifying the hypothesis that G depends on distance. The measurements were made with a highly sensitive torsion balance and an electronic indicating system. The values obtained are $G(r_1)/G(r_0)=1.003 \pm 0.006$ and $G(r_2)/G(r_0)=0.998 \pm 0.013$ (the limits correspond to the level of one standard deviation). These results do not confirm the experimental data of D. I. Long [Nature **260**, 417 (1976)], according to which spatial variations of G do exist. The possible imitating effects are analyzed and prospects for other procedures of experimentally verifying the indicated hypothesis are discussed.

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1. INTRODUCTION

The possible existence of not only temporal (in accordance with the well-known hypothesis of Dirac et al.[1-3]) but also spatial variations of the gravitational constant G[4,5] is being discussed of late. The dependence of G on the distance follows, in particular, from the scalar-tensor variants of gravitation theory[6-8] if one adds to the Newtonian gravitational potential a term of the Yukawa-potential type

$$V(r)=-\frac{G_\infty M}{r}(1+\alpha e^{-\mu r}), \tag{1}$$

where $G_\infty=G(r\to\infty)$, while α and μ are constant quantities ($\alpha>-1$). Introduction of a potential of this form is connected also with the question of the rest mass of the graviton.[9,10]

Thus, we are dealing not with post-Newtonian relativistic corrections[1)] but with an effect that takes place even in weak fields $GM/rc^2\ll 1$. Following Refs. 6–8, we shall adhere to the phenomenological model (1). In this case, the gravitational constant G in Newton's gravitation law is a function of the distance between the interacting masses:

$$G(r)=G_\infty[1+\alpha(1+\mu r)e^{-\mu r}], \tag{2}$$

from which it follows that for small "laboratory" distances $G=G_0=G_\infty(1+\alpha)$ (at $\mu r\ll 1$), while for large "cosmic" distances $G=G_\infty$ (at $\mu r\gg 1$).

Within the framework of the considered hypothesis, a substantial difference between G_∞ and G_0 is admissible. In particular, in Refs. 7 and 8 they obtained a theoretical value $\alpha=\frac{1}{3}$, which yields $G_\infty/G_0=0.75$. It is assumed here that the characteristic length μ^{-1} can amount to 10 m $<\mu^{-1}<$ 10 km.

The presented relations do not contradict the existing experimental data, since the gravitational constant, starting with Cavendish's experiments, was measured only for distances 5 cm $<r<$ 50 cm.[11] At distances $r>10^3$ km (according to astronomical observations of the motion of celestial bodies) only the product of G by the mass of the body was determined accurately, and for distances 1 m $<r<10^3$ km there are no experimental data whatever concerning the gravitational constant.

The value of G_∞ can be obtained from the known values of $G_\infty M_\oplus$ and $G_\infty M_\odot$ (the geo-and heliocentric gravitational constants) only approximately: estimates made in Ref. 5 on the basis of the existing models of the internal structure of the earth and of the sun show that the difference between G_∞ and G_0 can reach 40% because of the low accuracy with which the masses $M_\oplus$ and $M_\odot$ are determined. Stronger limitations (a difference between G_∞ and G_0 not larger than 10%) were obtained in Ref. 12 in an analysis of the data on white dwarfs, with account taken of the theory of stellar evolution.

We describe below an experiment aimed at determining the possible $G(r)$ dependence in the distance interval 0.4 m $\leqslant r\leqslant$ 10 m.

2. EXPERIMENTAL SETUP AND MEASUREMENT PROCEDURE

In this experiment, in contrast to the classical experiments aimed at determining G, we compared the values of the gravitational constants for different distances. To this end we measured the moment of the gravitational attraction forces between two test bodies m, fastened to the ends of the rocker arm of a horizontal gradient meter, and a mass M located at a distance

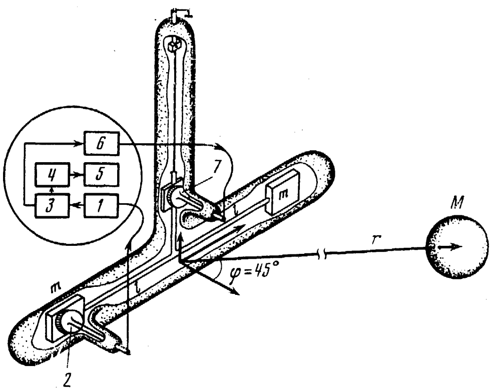

FIG. 1.

$r\gg l$ (Fig. 1). In such a scheme, the measured moment of the forces ΔP is given by

$$\Delta P=3G(r)mMl^2r^{-3}\beta. \tag{3}$$

Here $\beta\approx 1$ is a coefficient that takes into account the exact geometrical parameters of the installation.

It should be noted that in the present experiment it was necessary to measure with high accuracy a small quantity ΔP (~10^{-6} dyn·cm), which is smaller by a factor of at least 10^6 than the moment measured in the Cavendish experiments (see the review[11]).

ΔP was measured for two distances, $r_1\approx 3$ m and $r_2\approx 10$ m, with the corresponding masses $M_1\approx 60$ kg and $M_2\approx 600$ kg, respectively. In addition, a reference measurement of ΔP_0 was made at a small distance ($r_0\approx 4$ m, $M_0\approx 0.2$ kg). This made it possible to exclude from consideration the exact value of the sensitivity of the indication system, the mass m, and the length of the rocker arm. The registered quantity is the voltage ΔU at the output of the indication system, which is proportional to ΔP. In this case the following relation holds

$$\frac{\Delta U}{\Delta U_0}=\frac{\Delta P}{\Delta P_0}=\frac{G(r)M\beta}{G(r_0)M_0\beta_0}\left(\frac{r_0}{r}\right)^3, \tag{4}$$

from which the value of $G(r)/G(r_0)$ is in fact determined.

We used in the experiment a torsion balance with an oscillation period $\tau_0=910$ sec and an intrinsic relaxation time $\tau^*\approx 6\times 10^6$ sec. (Under the measurement conditions τ^* was decreased to $\approx 2\times 10^3$ sec by using electromechanical feedback.) The masses $m=10$ g and the rocker arm of length $2l=40$ cm were made of fused quartz. The rocker arm was suspended on a tungsten filament (length $L=31$ cm and diameter 30 μm) in a sealed glass vacuum chamber at a pressure $p\sim 5\times 10^{-8}$ Torr. The installation was placed in a screened active thermostat whose temperature was maintained at 30° ±0.02 °C.

The motions of the rocker arm were registered with a capacitive displacement sensor[13] *1* (the capacitor was made up of a stationary plate *2* and the flat face of one of the masses m). The signal from the sensor was fed through a dc amplifier *3* and an integrating network *4* to a digital recording system *5*. To decrease the influence of seismic noise, the signal from the output of the amplifier 3 was fed through a narrow-band amplifier 6 to feedback plates 7. The introduction of this feedback made it possible, by active damping of the parasitic pendulum oscillations, to decrease the effective noise temperature of the balance from $T_{eq} \approx 10^5$ K to $\approx 1.3 \times 10^3$ K. The use of a high-sensitivity method for indicating small angular displacements $\sim 10^{-8}$ rad and the decrease of T_{eq} made it possible to increase substantially the sensitivity of the system: with the described balance we could register a force $F \approx 2 \times 10^{-10}$ dyn acting on the test masses (i. e., an acceleration a $\approx 2 \times 10^{-11}$ cm/sec^2) with a signal separation time $\sim 10^4$ sec, a sensitivity comparable with that attained in the best experimental installations of similar type.[14]

The measurements were made in a basement room at the physics deparment of the Moscow State University. The masses M were displaced periodically, with a period $\tau_c \approx \tau_0$ (resonant action). The measurement time was $10\ \tau_c = 9 \times 10^3$ sec. The statistical reduction of the signal consisted of determining the amplitude ΔU of the harmonic with period and phase corresponding to the phase of the external action,[15] which is equivalent to the operation of synchronous detection.

3. MEASUREMENT RESULTS AND IMITATING EFFECTS

In accordance with (4), the quantities $A_i = G(r_i)/G(r_0)$ are expressed in the form

$$A_i = \frac{\beta_0 M_0 \Delta U_i}{\beta_i M_i \Delta U_0}\left(\frac{r_i}{r_0}\right)^3. \tag{5}$$

The numerical values, obtained as a result of the measurements, of the amplitudes of the harmonics ΔU_i and of the parameters r_i, M_i, β_i/β_0 (i = 0, 1, 2) are listed in the table. Substituting these data in (5), we obtain the final results for A_i:

$$A_1 = 1.003 \pm 0.006, \quad A_2 = 0.998 \pm 0.013.$$

For all quantities, the confidence limits correspond to one standard deviation, and the principal error of A_i is due to the error in the determination of the moments ΔP_i of the forces.

To compare the results with the hypothetical relation (2) we assume (just as in Refs. 6–8) that 10 m $< \mu^{-1} <$ 10 km. In this case at $r \leq 10$ m formula (2), accurate to terms $\sim \mu^2 r^2$, takes the form

$$G(r) = G_\infty[1 + \alpha(1 - 0.5\mu^2 r^2)], \tag{6}$$

whence

$$A = \frac{G(r)}{G(r_0)} = 1 - \frac{\alpha\mu^2 r_0^2}{2(1+\alpha)}\left(\frac{r^2}{r_0^2} - 1\right). \tag{7}$$

From the experimental values of A_i we can construct the regression line

TABLE I.

i	ΔU_i, mV	M_i, kg	r_i, cm	β_i/β_0
0	302.1±0.8	0.2013±0.0001	42.06±0.05	1
1	335.2±1.0	56.66±0.02	295.8±0.3	1.367±0.001
2	102.4±1.0	594.9±0.5	984.0±2.5	1.472±0.002

$$A = \eta + \lambda x, \tag{8}$$

where $x = r^2/r_0^2 - 1$, and η and λ are parameters. It follows therefore that A is constant at $\lambda = 0$, i. e., G is independent of distance. The calculation of the regression-line parameters (see, e. g., Ref. 16) yields $\lambda = (-0.4 \pm 2.5) \times 10^{-5}$. Comparing (7) and (8), we obtain an estimate of the combination of the parameters α and μ:

$$\alpha\mu^2 r_0^2/(1+\alpha) = (+0.8 \pm 5.0) \cdot 10^{-5}. \tag{9}$$

For example, at $\mu^{-1} = 20$ m we have $-0.09 \leq \alpha \leq 0.15$, which corresponds to the estimate $0.87 \leq G_\infty/G_0 \leq 1.09$. On the other hand if $\alpha = \frac{1}{3}$ (according to Refs. 7 and 8), then $\mu^{-1} > 28$ m.

These estimates showed that within the limits of the experimental accuracy there is no $G(r)$ dependence in the distance range up to 10 m. However, the accuracy attained in the experiment does not answer unequivocally the question of whether such a dependence is nonexistent for distances $r \gg 10$ m.

The measured values of A_i are represented in Fig. 2, which shows for comparison also the experimental values of A_0' and A_1' in accordance with the data of Ref. 17. Thus, our results do not confirm the conclusions drawn in Ref. 17 that a $G(r)$ dependence exists.

We present estimates of the effects that might imitate in the described experiment the $G(r)$ dependence. Foremost among them are effects that act with the frequency and phase as the useful signal; the influence of the deformation of the floor and walls of the laboratory by the displacements of the large masses of M, and the presence of magnetic interaction between the masses. In addition, variations of the electrostatic attraction force between the masses m and the walls of the vacuum chamber are significant.

A. Periodic deformations of the floor and walls of the laboratory, due to the displacement of the masses M, lead to displacements of the rocker arm relative to the vacuum chamber. In this case the change of the distance between the plates of the capacitive sensor leads to the appearance of a signal that imitates the action of the force moment ΔP_{def}. Using the expression for the bending of a diaphragn by a force applied to the center,[18] we obtain an upperbound estimate

$$\Delta P_{def} = \frac{6mlLF_M R(1-\sigma^2)}{\tau^* \tau_0 h^3 E}\gamma \approx 2 \cdot 10^{-10}\ \text{dyne-cm}. \tag{10}$$

Here $F_M = 6 \times 10^8$ dyn is the weight of the largest mass

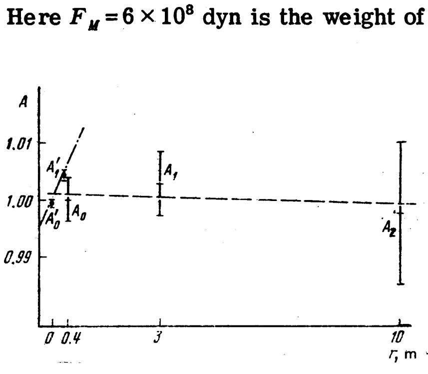

FIG. 2.

M; $R=5$ m and $h=30$ cm are the radius and thickness of the floor; $E\approx 10^{12}$ dyn/cm^2 and $\sigma\approx 0.3$ are Young's modulus and the Poisson coefficient (reinforced concrete); $\gamma\approx 10^{-3}$ is the coefficient for recalculating the slanting of the floor into the slanting of the laboratory wall (the weights were secured to a wall of thickness ~1 m.

Since $\Delta P_2=5\times 10^{-7}$ dyn·cm, the possible systematic error of A_2 does not exceed $\Delta A_2=\Delta P_{def}/\Delta P_2\approx 4\times 10^{-4}$.

B. Magnetic interaction between the masses m and M in the presence of ferromagnetic impurities in their volume or on their surface can lead to the appearance of an imitating force moment ΔP_{magn}. To estimate this effect, control measurements were made of the magnetic susceptibility χ of the masses m (we measured the force acting on the mass m in an inhomogeneous magnetic field). The obtained value $\chi\approx -3\times 10^{-6}$ indicated that there were no ferromagnetic impurities. In this case the presence of even an appreciable magnetic moment of the masses M cannot exert a noticeable influence on the position of the balance. For example, a magnet with volume $v_1\leqslant 10^3$ cm^3 and residual magnetization $B=10^4$ G located in the mass M_2 would produce at a distance $r=r_2=10$ m a parasitic torque

$$\Delta P_{magn}=\frac{12lv\chi}{r^7}\left(\frac{Bv_1}{4\pi}\right)^2\leqslant 2\cdot 10^{-12}\text{ dyn}\cdot\text{cm} \tag{11}$$

at $v=4.6$ cm^3 (the volume of the mass m).

The corresponding systematical error of A_2 is $\Delta A_2=\Delta P_{magn}/\Delta P_2\leqslant 4\times 10^{-6}$. For the mass M_1 at $v_1\leqslant 10^2$ cm^3 we have $\Delta P_{magn}\leqslant 9\times 10^{-11}$ dyn-cm and accordingly $\Delta A_1=\Delta P_{magn}/\Delta P_1\leqslant 5\times 10^{-5}$.

C. A substantial source of errors in measurements with a highly sensitve balance is the electrostatic interaction between sections of the surfaces of the masses, of the rocker arm, and of the vacuum chamber. At a potential difference $U\approx 1$ V, the force acting between plates of area $S\approx 1$ cm^2 separated by a distance $d\approx 1$ cm is $F\approx SU^2/8\pi d^2\approx 10^{-7}$ dyn. The corresponding moment is $\Delta P_{el}\approx Fl\approx 2\times 10^{-6}$ dyn·cm, which is comparable with ΔP_i.

The character of the action of the electrostatic forces depends on many factors, and their analytic calculation is quite complicated. The main means of combating these effects is therefore the use of conducting coatings on the moving parts of the balance in the vacuum chamber. In the described construction the quartz rocker arm, the masses m, and the inner surface of the glass chamber were coated with a layer of silver ~1 μm thick and were grounded.

It should be noted that the measurement method used in Ref. 17, wherein the gravitational attraction forces were compensated for by electrostatic forces, can result in a substantial error. In our opinion, the effect observed by the authors due to unaccounted-for variations of the contact potential difference between the compensating plates.[19]

4. POSSIBLE VARIANTS OF EXPERIMENTS AT DISTANCES $r\gg 10$ m

As already noted, the situation is possible wherein $\mu^{-1}\gg 10$ m. In this case, to check on the hypothetical relation (2) it is necessary to measure G at distances ~100 m and more.

Rigid-body detectors of gravitational waves can be used for this purpose.[13,20] The experiment is set up outside the wave zone in accordance with the "transmitter–receiver" scheme, so that periodical Newtonian gravitational fields with frequency ~10^2–10^4 Hz can be registered. Estimates show that second-generation high-sensitivity gravitational antennas (if ever developed) will make it possible to determined by this method the value of G at distances ~100 m with accuracy up to 0.1%.[21]

A static experiment is also possible, using large distances and masses: the gravitational constant can be measured by comparing the acceleration due to the force of gravity on the surface of the ocean and deep inside the ocean by means of modern highly sensitive gravimeters.[22] Attempts of such measurements were made back in the 19th century (see the review in Ref. 11), but their accuracy was quite low.

In addition, experiments in outer space are possible. Data on the value of G at distances ~1–10 km can be obtained using a gravimeter on board a spaceship moving near small bodies of the solar system, for example on an orbit around Mars near its satellites Phobos or Deimos.[23]

The realization of these (and possibly other) experiments will make it possible to answer with greater reliability the question of whether spatial variations of the gravitational constant exist.

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[1)]Under laboratory conditions and reasonable experimental scales, the post-Newtonian corrections GM/rc^2 are of the order of 10^{-24}–10^{-26}, and consequently make a negligibly small contribution in the measurement of G.

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Translated by J. G. Adashko

Polarized photons from silicon single crystal in the 31-GeV electron beam of the Serpukhov proton accelerator

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A beam of tagged photons emitted coherently is obtained from a silicon single crystal placed in an electron beam from the Serpukhov proton accelerator. The electron energy is $E_e = 31$ GeV, the beam intensity is 4×10^4 particles per pulse of duration 1.7 sec. The photon intensity in each of five almost equal energy intervals in the range $k = 8.2$–24.2 GeV is $I \sim (10^{-1}$–$10^{-2})\gamma/e^-$, and the linear polarization is estimated at $P \sim 50$–20%. A method is described for aligning the single crystal in the proton-accelerator electron beam. Unexplained narrow radiation intensity peaks are observed when the single-crystal orientation is varied.

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1. INTRODUCTION

Proton synchrotrons are presently used extensively as sources of electrons and unpolarized photons with energies unattainable in the existing electron accelerators.[1-5] Questions involving the production of polarized-photon beams in a new high-energy region are therefore extensively discussed in recent years.[6-11] The most promising methods for protons accelerators for these purposes are those using effects in single crystals, such as coherent bremsstrahlung of electrons[11,12] and selective absorption of bremsstrahlung photons.[13,14] According to theoretical estimates, these methods will make it possible to obtain linearly polarized photons with respective energies 0.2–0.7 of the electron energy also at the end of their bremsstrahlung spectrum. Linear polarization of photons can be transformed into circular polarization by using a second single crystal of suitable thickness.[15]

The use of coherent bremsstrahlung of electrons to generate polarized photons in proton accelerators has distinctive features connected with the angular divergence of the produced electron beams when their intensity is relatively low, the transverse dimensions are large, and have noticeable nonmonochromaticity. Collimation of the electron beam and a decrease of the electron energy spread make it possible in this case to obtain low-intensity fluxes of quasimonochromatic polarized photons, which can be used only in experiments with bubble chambers. The effective use of the electron beam itself is exceedingly low in this case. A substantial increase in the effectiveness can be obtained by using the method of tagging polarized photons in a wide energy range of the bremsstrahlung spectrum. Beams of tagged polarized photons in proton accelerators make possible experiments with the use of counting and recording apparatus.

We present here a complete description of an experiment, with the Serpukhov accelerator on the production of a beam of tagged linearly polarized photons by the method of coherent bremsstrahlung of electrons in a silicon single crystal, and the results of an analysis of the obtained data.

2. EXPERIMENTAL SETUP

The magneto-optical electron channel 14 E, in which the experiment was performed, is described in Ref. 2.

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