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2025 • 3

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CONTENTS

PHYSICS

CHEMISTRY

МАЗМҰНЫ

ФИЗИКА

ХИМИЯ

СОДЕРЖАНИЕ

ФИЗИКА

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Abstract. The article discusses methods for determining the gravitational constant G and factors affecting the accuracy of measuring this fundamental constant. G was determined using two methods and the accuracy of the results obtained was analyzed. The purpose of the article is to analyze the most effective methods for measuring G and to find ways to further improve the accuracy of determining the gravitational constant. Two main approaches to measurement are described: a method based on the study of the external photoelectric effect, and a resonance method using a Cavendish torsion balance adapted to improve accuracy by simultaneously measuring the acceleration of gravity at the points under study. The second part of the article presents the results of experiments performed using the two above-mentioned methods. Particular attention is paid to the correlation between the measured value of G and the characteristics of the local gravitational background. Based on the data obtained, an assumption was made about a possible dependence of the gravitational constant value on the configuration and intensity of the local gravitational field. A conclusion was made about the need to revise traditional methods of measuring G, with an emphasis on developing new experimental schemes that can take into account the influence of local gravity and minimize the influence of unaccounted factors. The importance of an integrated approach, which involves the simultaneous determination of gravity and the gravitational constant, is emphasized, which can increase the reliability and consistency of the results obtained.

Keywords: gravitational constant, torsion balance, Cavendish experiment, moment of inertia, external photoelectric effect, resonance method

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ГРАВИТАЦИЯЛЫҚ ТҰРАҚТЫНЫ АНЫҚТАУ

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Аннотация. Мақалада G гравитациялық тұрақтысын анықтау әдістері және осы негізгі тұрақтыны өлшеу дәлдігіне әсер ететін факторлар қарастырылады. G анықтау екі әдіспен жүргізілді және алынған нәтижелердің дәлдігі талданды. Мақаланың мақсаты G өлшеудің ең тиімді әдістерін талдау және гравитациялық тұрақтыны анықтаудың дәлдігін одан әрі жақсарту жолдарын табу. Өлшеудің екі негізгі тәсілі сипатталған: сыртқы фотоэффектіні зерттеуге негізделген әдіс және зерттелетін нүктелердегі ауырлық күшінің үдеуін бір уақытта өлшеу арқылы дәлдікті жақсартуға бейімделген Кавендиш бұралу балансын қолданатын резонанс әдісі. Мақаланың екінші бөлімінде жоғарыда аталған екі әдісті қолдану арқылы жүргізілген тәжірибелердің нәтижелері берілген. G-тің өлшенетін мәні мен жергілікті гравитациялық фонның сипаттамалары арасындағы корреляцияға ерекше назар аударылады. Алынған мәліметтер негізінде гравитациялық тұрақты мәннің жергілікті гравитациялық өрістің конфигурациясы мен қарқындылығына ықтимал тәуелділігі туралы болжам жасалды. Жергілікті гравитацияның әсерін ескеретін және есепке алынбаған факторлардың әсерін барынша азайта алатын жаңа тәжірибелік схемаларды әзірлеуге баса назар аудара отырып, G өлшеудің дәстүрлі әдістерін қайта қарау қажеттілігі туралы қорытынды жасалды. Алынған нәтижелердің сенімділігі мен дәйектілігін арттыра алатын ауырлық күші мен гравитациялық тұрақтыны бір уақытта анықтауды қамтитын кешенді тәсілдің маңыздылығы атап өтіледі.

Түйін сөздер: гравитациялық тұрақты, бұралу балансы, Кавендиш тәжірибесі, инерция моменті, сыртқы фотоэффект, резонанс әдісі

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ОПРЕДЕЛЕНИЕ ГРАВИТАЦИОННОЙ ПОСТОЯННОЙ

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Аннотация. В статье рассмотрены методы определения гравитационной постоянной G и факторы влияющие на точность измерения данной фундаментальной константы. Выполнены определения G двумя методами и анализ точности полученных результатов. Целью статьи является анализ наиболее эффективных методов измерения G и поиск путей дальнейшего повышения точности в определении гравитационной постоянной. Описаны два основных подхода к измерению: метод, основанный на изучении внешнего фотоэффекта, и резонансный метод с применением крутильных весов Кавендиша, адаптированный для повышения точности за счёт одновременного измерения ускорения свободного падения в исследуемых точках. Во второй части статьи представлены результаты экспериментов, выполненных двумя вышеназванными методами. Отдельное внимание уделяется корреляции между величиной измеренного значения G и характеристиками локального гравитационного фона. На основе полученных данных высказано предположение о возможной зависимости значения гравитационной постоянной от конфигурации и интенсивности локального гравитационного поля. Сделан вывод о необходимости пересмотра традиционных методик измерения G, с акцентом на разработку новых экспериментальных схем, способных учитывать влияние локальной гравитации и минимизировать влияние неучтённых факторов. Подчёркнута важность комплексного подхода, предполагающего одновременное определение силы тяжести и гравитационной постоянной, что может повысить достоверность и согласованность получаемых результатов.

Ключевые слова: гравитационная постоянная, крутильные весы, эксперимент Кавендиша, момент инерции, внешний фотоэффект, резонансный метод

Introduction. The gravitational constant G is involved in Newton's equation and Einstein's general theory of relativity, and is also used to determine the masses of planets and the force of interaction between objects in the micro- and macroworld. However, despite its fundamental role in science, the gravitational constant remains one of the least accurately known physical constants. Unlike other constants, such as the speed of light or Planck's constant, the value of G is difficult to measure experimentally, since the results of various laboratory experiments, even with high accuracy, still show discrepancies that exceed the expected errors. This uncertainty not only represents an interesting experimental problem, but also limits the accuracy of calculations in a number of fundamental and applied areas of physics.

The English scientist Henry Cavendish first determined the value of the gravitational constant in 1798 using a torsion balance. At that time, the value of G was obtained as $6{,}754\times 10^{-11}\,\mathrm{m}^3\mathrm{kg}^{-1}\mathrm{c}^{-2}$ and its relative error did not exceed one percent. Since the Cavendish experiment, various methods and approaches to measuring the gravitational constant have been used and proposed. These include early torsion balance refinements with angular acceleration feedback (Gundlach & Merkowitz, 2000), updated reviews of fundamental constants (Mohr et al., 2016), improved determinations with dual methods (Quinn et al., 2013), the torsion method (Luo et al., 2005) and seconds pendulum method (Newman et al., 2006), experiments using atomic interferometry (Bertoldi et al, 2006), experiments in space, away from interfering effects (Brown, 2023). Some of these methods may require complex experimental conditions and give results with varying accuracy. We will present the most interesting and highly accurate experiments performed in recent decades and their results.

A brief review of the literature on the definition of the gravitational constant. As noted by G. Rosi (Rosi et al., 2014), the first accurate determination of G using laser-cooled atoms and quantum interferometry to study gravity is reported. The basic idea of the experiment is to use an atomic interferometer as a gravity sensor and precisely known masses as the source of the gravitational field. By accurately measuring the acceleration of the atoms created by the source mass and knowing the mass distribution, it was possible to determine the value of the gravitational constant G. The experiment yielded a value of $G = 6.67191(99) \times 10-11\ \mathrm{m}^3\ \mathrm{kg}^{-1}\ \mathrm{s}^{-2}$, with a relative uncertainty of 150 ppm, which is 1.5 combined standard deviations from the current recommended value of the Committee on Data for Science and Technology (CODATA).

Also known are the results of measuring the gravitational constant using scales and 13 tons of mercury (Schlamminger et al., 2014), which were previously performed by S. Schlamminger from the University of Zurich and published in 2006. In this experiment, two large cylinders, each filled with mercury weighing 6760 kg, created the gravitational field. The joint work of scientists led to the value $G = 6.674\,252(122) \times 10^{-11}\ \mathrm{m}^3\ \mathrm{kg}^{-1}\mathrm{s}^{-2}$. The relative standard uncertainty of the measurement was 18×10^{-6}.

Experiments performed by Chinese scientists (Li et al., 2018) in collaboration with a Russian researcher provide another contribution to the challenging task of measuring the value of G. By performing two independent determinations of G in torsion pendulum experiments, using the swing time method and the angular acceleration feedback method, the obtained G values are 6.674184×10^{-11} and $6.674484\times10^{-11}\ \mathrm{m}^3\ \mathrm{kg}^{-1}\mathrm{s}^{-2}$ with relative standard uncertainties of 11.64 and 11.61 ppm, respectively. These values have the smallest uncertainties reported to date, and both agree with the latest recommended value within two standard deviations.

Another experiment to measure the gravitational constant G, based on cold atom interferometry, was carried out in 2018 by Italian and Dutch scientists (Lamporesi et al., 2008). The experiment resulted in a value of $G = 6.667\ 10^{-11}\ m^3kg^{-1}s^{-2}$. The statistical uncertainty is estimated at $\pm 0.011\ 10^{-11}\ m^3kg^{-1}s^{-2}$ and the systematic error is $\pm 0.003\ 10^{-11}\ m^3kg^{-1}s^{-2}$. The long-term stability of the device and the signal-to-noise ratio demonstrated here open up good prospects for further improving the measurement accuracy.

In recent years, large variations in the measured values of G have led scientists to question whether G is really a constant at all. Some theories and studies (Kordi, 2009) suggest a possible variation of the gravitational constant on cosmological or quantum scales. Although the vast majority of scientists believe that G is a constant and that, the variations are caused by large systematic measurement errors. The current situation with conflicting values of the gravitational constant highlights the need for additional measurements and analysis of sources of measurement errors, including the influence of the gravitational field at the observation points.

Methods and materials. The authors of this article previously determined the gravitational constant using the acceleration method (Shalenov et al., 2024), with the Atwood machine. As a result, the obtained value of G was equal to $6.670679 \times 10^{-11}\ m^3kg^{-1}s^{-2}$, the error of which was $0.0018105 \times 10^{-11}\ m^3kg^{-1}s^{-2}$, compared with the value of G currently accepted by the Committee on Data for Science and Technology. It was concluded that it is necessary to improve the accuracy of measuring the time of movement of the weights to obtain a more accurate value of G using this method.

In order to analyze the sources of errors affecting the experiment to determine G and to obtain the true value of this constant, two more experiments were performed. One of which was performed based on the study of the external photoelectric effect, and the other by the resonance method using the Cavendish torsion balance.

The first method of determining the gravitational constant is based on the study of the photoelectric effect method, by means of which Planck's constant is first determined, and then G itself. The photoelectric effect is studied on an installation that consists of: 1) a photocell and an incandescent lamp placed on an optical bench; 2) a digital microammeter and voltmeter, combined with a rheostat into one electronic unit of devices (Fig. 1).

Figure 1. Optical bench and electronic unit for studying the photoelectric effect

The operation diagram of the setup for studying the photoelectric effect is shown in Figure 2. The vacuum photocell is enclosed in a protective casing with a window and is a glass bulb, half of which is coated on the inside with a thin layer of alkali metal. This layer is the cathode of the photocell. The anode is a metal ring located in the center of the bulb. The light source is a halogen incandescent lamp. To regulate the brightness, the voltage U is varied by the knob located on the left side of the front panel of the electronic unit. Monochromatic radiation is obtained using light filters fixed in a rotating frame (the wavelengths of the light filters are indicated on the setup). The photocurrent is measured by a digital microammeter - a digital display located on the left on the front panel of the electronic unit. The voltage on the photocell is changed by rotating the rheostat knob (the right side of the front side of the electronic unit) and measured by a digital voltmeter - a digital display located on the right on the front panel of the electronic unit. Switching between the delay and acceleration voltage modes is performed using a polarity switch located at the bottom of the electronic unit panel.

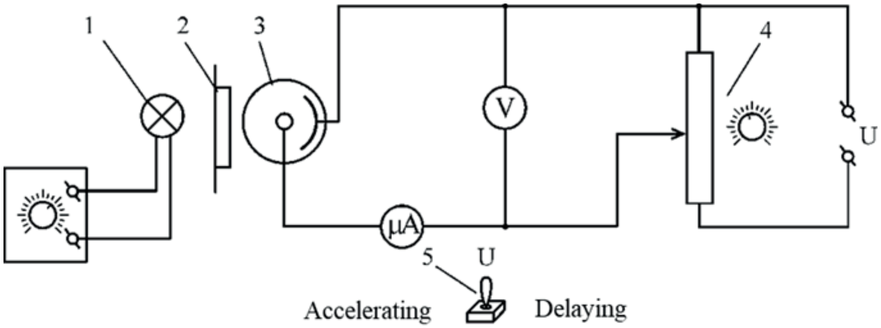

Figure 2. Schematic diagram of the setup for studying the photoelectric effect: 1 – incandescent lamp; 2 – light filters in a frame; 3 – photocell; 4 – rheostat; 5 – polarity switch.

The experiment is performed in the following order: a light source, a set of light filters and a photocell are placed on the optical bench. For a light filter with λ =505 nm, the maximum current is set in the incandescent lamp. By changing the position of the photocell on the optical bench relative to the incandescent lamp, the photocurrent I=0.6 μA (U=0) is set. Then the operating mode is switched to the holding voltage Uз, and zero value of the photocurrent is achieved (I=0). The value of the holding potential is read from the digital display of the unit and entered into the table. Then, steps 2-3 are repeated for other light filters without changing the position of the photocell.

The results are processed in the following order: calculate the frequencies λ transmitted by the light filters; plot a graph of the linear dependence U_3= f(n . Extrapolate the resulting straight line until it intersects the ordinate axis. From the graph, find the cutoff frequency n_0 (at n =n_0, U_3=0B) and the delay voltage (at n =0):

$$U_3 = A/e \tag{1}$$

Then, the work function of the electron A from the cathode is calculated using the formula:

$$A = U_{\text{з}} \cdot 1{,}6021766208 \cdot 10^{-19} (J) \qquad (2)$$

Planck’s constant is found from the expression:

$$h = A/v_0 \qquad (3)$$

From the value of Planck’s constant, the gravitational constant G is found as a function of h (Mercier, 2016):

$$G = \frac{2\pi r_e^2 c^3 \alpha^{19}}{\beta h} \qquad (4)$$

where c is the speed of light in a vacuum; α is the fine structure constant; r_e is classical electron radios; β=3-√5, is the ratio between the rate of expansion of the material universe and the rate of expansion of the luminous universe.

The second method of determining the gravitational constant was performed using a Cavendish torsion balance, with simultaneous observation of the acceleration of gravity at the point of standing. It is believed that the location of the observation point does not affect the value of the gravitational constant G, since it is a universal constant and does not depend on the location of the observer. However, the desire of some scientists (Feldman et al., 2016) to measure G in deep space was motivated precisely by the goal of eliminating the influence of Earth’s gravity on the course of the experiment.

As some researchers believe, a more precise value and the possibility that G may vary with time, location, or the type of matter involved could be related to improvements in Einstein’s general theory of relativity, including quantum gravity. To find out if there is a correlation between the change in gravity and the G number, we performed an experiment at four stations located at different altitudes above sea level in the city of Almaty and the nearby Trans-Ili Alatau Mountains.

The experiment was performed using the resonance method with a Cavendish balance, with simultaneous measurement of the gravity increment Δg (relative to the original gravimetric point) at the observation point with a CG-6 AUTOGRAV relative gravimeter (Fig. 3).

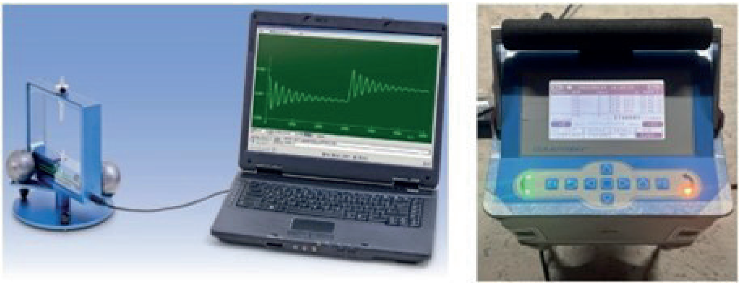

Figure 3. Cavendish torsion balance and CG-6 AUTOGRAV™ gravimeter

In the controlled resonance method, the large balls are rotated back and forth between two extreme positions so that the force of gravity between the large balls and the boom always does positive work on the balance, and the amplitude increases until the energy loss from damping is equal to the work done by gravity. To determine G, it is necessary to know the damping coefficient of the balance, which is determined by measuring the amplitude attenuation during free oscillation of the balance. The gravitational constant is determined from the expression:

$$G = K\theta_D R^2/(2Mmd) \qquad (5)$$

where

K – torsion spring constant;

Θ_D– change in the boom equilibrium angle when turning large masses from the central to one of the extreme positions;

R – distance between the centers of the large and small balls;

M, m – masses of the large and small balls;

d – distance from the axis of rotation to the center of the small sphere.

The torsion constant is found by the formula:

$$K = 4\pi^2 I/T^2 \qquad (6)$$

where

T – period of oscillation of the boom;

I – total moment of inertia of two small spheres.

To determine the change in the balance angle Θ_D, a minimum of three adjacent turning points Θ_i are measured when the balance is resonantly driven and three adjacent turning points when the balance is in a free-damping state. Each set of three measurements requires the balance to oscillate for one complete cycle, which, depending on the length of the tungsten fiber, is about 4 minutes or less. The damping coefficient x is then determined from the expression:

$$x = 1 - (\theta_1 - \theta_N)/(\theta_1 - \theta_2 + \theta_3 - \theta_4 + \cdots - \theta_{N-1}) \qquad (7)$$

The value of the angle Θ_D is calculated using the following formula, taking into account the value of the coefficient x:

$$\theta_D = [(1 - x)(\ \theta_1 - \theta_2 + \theta_3 - \theta_4 + \cdots \theta_N) - \theta_1 + x\theta_1 N]/[(N-1)(1+x)] \qquad (8)$$

When calculating the gravitational constant in order to achieve the best balance, corrections are introduced for the attraction of the large sphere to the distant small sphere and a correction for the gravitational moment acting on the beam.

Results and discussion. In the first method of determining G based on the study of the photoelectric effect, the cutoff frequencies n_0 were determined, corresponding to the wavelengths of light λ transmitted by light filters (Table 1).

Table 1. Results of studying the photoelectric effect and determining the delay voltage $\overline{U}_{з}$

λ, нм	595	590	540	525	505
ν,*10^{14} Гц	5.038529	5.081228	5.551712	5.710333	5.936484
$U_{з}$, В	0.053	0.071	0.266	0.331	0.425
Borderline $\overline{U}_{з}$ = 2.031136B		Cutoff frequency n			

A graph of the linear dependence U3= *f(ν)* was constructed (Fig. 4) and the cutoff frequency n_0 (at n= n_0, U_3=0V) and the arresting voltage U3 (at n= 0) were determined from the graph, and the following were calculated: the work function of the electron from the cathode A, Planck's constant h and the value of the gravitational constant G according to formulas (2)-(4). As a result, G ≈ $6.67227 \cdot 10^{-11}$ m^3 kg^{-1} c^{-2} was obtained, with an accuracy of $0{,}0004731 \cdot 10^{-11}$ m^3 kg^{-1} c^{-2} ,

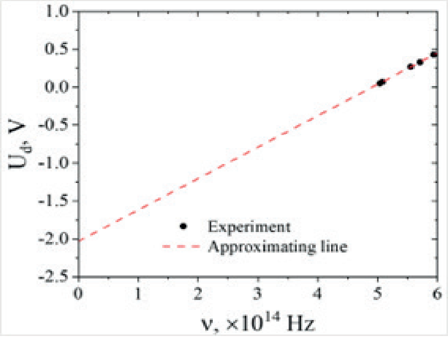

Figure 4. Linear dependence graph U_3= f(ν)

In the second method of measuring G, the observation points were at different heights (Fig. 5) and, accordingly, had different gravity values.

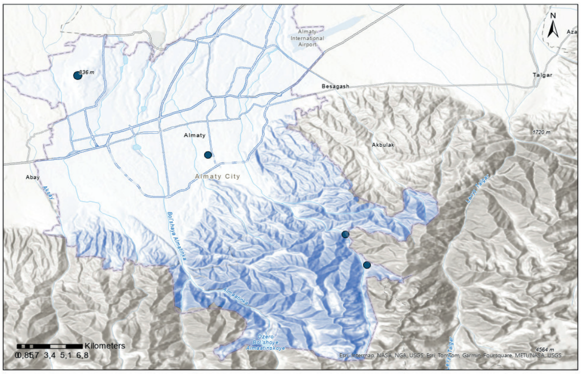

Figure 5. Layout of observation stations

At this stage of the research, it was sufficient to use four observation points, which made it possible to obtain information about the presence of a correlation between the values of the gravitational constant and the increment of gravity at the standing points. During the experiment, measures were taken to reduce the influence of external factors such as temperature changes, vibrations and electromagnetic interference by conducting the experiment in a closed room at a constant room temperature and in the absence of foreign gravitational objects and power sources. The torsion balance and gravimeters were not connected to external power sources during the experiments. The results of determining G by the resonance method at four stations and the measured gravity anomalies are given in Table 2.

The G values obtained at different altitudes differ from each other and correlate with the values of the gravity increments at the observation points, confirming the fact that the result of the experiment on measuring G is affected by the gravity at the observation point. Moreover, the greater the gravity value, the greater its influence on the accuracy of measuring G.

Table 2. Results of determining G by the resonance method at four stations

№	Latitude B, Longitude L	Height of the point, H	Gravity increment Δg, mGal	Gravitational constant G, $m^3\ kg^{-1}\ s^{-2}$	Accuracy of G determination, $m^3\ kg^{-1}\ s^{-2}$
1	43.314419 76.809555	835.20	3977.944	$6.670372 \cdot 10^{-11}$	$-0{,}000588 \cdot 10^{-11}$
2	43.236290 76.931526	848.01	3947.484	6.670815Ч	$-0{,}000522 \cdot 10^{-11}$
3	43.158056 77.059662	1685.20	3780.964	$6.672358 \cdot 10^{-11}$	$-0{,}000291 \cdot 10^{-11}$
4	43.127500 77.080005	2295.80	3662.180	$6.673542 \cdot 10^{-11}$	$-0{,}000113 \cdot 10^{-11}$

To reliably establish the relationship between high G and measured gravity, it is necessary to conduct an experiment at a significant number of stations located at different altitudes above sea level. This experiment will allow us to determine the correction required to the measured G value to eliminate local gravity.

A preliminary analysis of the available data reveals a correlation between the G value and local gravity that is quite close to linear (Fig. 6).

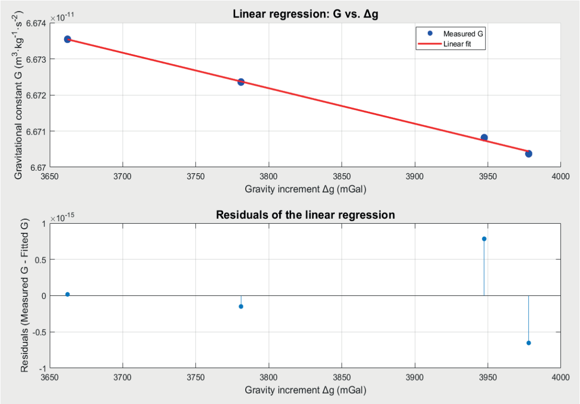

Figure 6. Relationship between G and local gravity

Conclusion. In general, the values of the gravitational constant obtained by the three methods differ from each other and coincide with the value adopted by the Committee (CODATA) within two decimal places. The reasons for the discrepancies in the experimental results are insufficient measurement accuracy and the influence of external noise sources, including the gravitational field at the point of the experiment. To enhance the accuracy of the results, it is essential to account for the influence of external error sources as thoroughly as possible and to conduct a preliminary estimation of measurement accuracy based on the desired precision in determining the value of G. It is also recommended to use fundamentally different approaches to determining the gravitational constant for comparative analysis and identifying a more accurate method for determining this constant. Taking into account that the gravitational constant is measured on the surface of the Earth, it seems relevant to jointly measure large G and small g in order to take into account the influence of local gravity.

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