МІНІСТЕРСТВО ОСВІТИ І НАУКИ УКРАЇНИ

Тернопільський державний технічний університет
імені Івана Пулюя

Кафедра фізики

PHYSICS LABORATORY

ФІЗИКА:
ЛАБОРАТОРНИЙ ПРАКТИКУМ

для студентів - іноземців

Тернопіль

2016

Physics laboratory / Kovalyuk B.P., Skorenkyy Yu.L. Nikiforov Yu.M. - Ternopil, TNTU, 2016.- 130 p.

Present book contains theory, description of experimental equipment, procedure and analysis recommendations to the physics laboratory experiments for foreign students studying in Ukraine.

Фізика: лабораторний практикум / Ковалюк Б.П., Скоренький Ю.Л., Нікіфоров Ю.М. - Тернопіль, ТНТУ, 2016.- 130 с.

Навчальний посібник містить теоретичні основи, опис експериментального устаткування та методичні вказівки до виконання лабораторних робіт з фізики студентів-іноземців, які навчаються в Україні.

Укладачі: **Ковалюк Богдан Павлович**
Скоренький Юрій Любомирович
Нікіфоров Юрій Миколайович,

Рецензенти:

д.ф.-м.н. **Дідух Леонід Дмитрович**, професор кафедри фізики Тернопільського національного технічного університету імені Івана Пулюя;

к.ф.-м.н. **Грицюк Петро Михайлович**, професор, завідувач кафедри економічної кібернетики Національного університету водного господарства (м. Рівне);

д.т.н. **Рудяк Юрій Аронович,** завідувач кафедри медичної фізики діагностичного та лікувального обладнання ДВНЗ „Тернопільський державний медичний університет імені І.Я. Горбачевського МОЗ України”

Рекомендовано до друку та використання в освітньому процесі Вченою радою ТНТУ, протокол № 3 від 26 квітня 2016 р.

CONTENTS

Preface

This manual is based on the authors' personal and professional experiences developed from teaching a three-semester course in Physics for international students over a couple of years.

The main aim of the textbook is to fill the still existing void for higher education Physics textbooks, especially the lab practicals, written in English by Ukrainian authors. The present Physics lab practical serves to provide a qualified teaching method, which meets the Bologna Process standards, as well as can be applied by academic departments in Ukrainian universities.

The primary purpose of the manual is to enable conformity and improve the practical Physics course materials being taught to Ukrainian and international students.

One of the difficulties that became evident during the process of preparing the present manual was the different levels of background knowledge of various international students. Each country has its own teaching and learning methods and strategies for Physics. Some of the international students did not take any preparatory courses before entering Ukrainian universities. Different mindsets toward education, the desire to achieve high scores even with moderate physics reasoning ability, and various levels of academic confidence among the students were taken into consideration, as well.

A thorough analysis of most popular Physics textbooks and secondary literature written in English and comparison with Ukrainian textbooks in terms of content, structure, and diagrams contributed to the emergence of this handbook.

Various information sources, such as the Internet, libraries, bookstores, numerous discussions with professors at the conferences and experts from the industry all confirmed our reasoning: a manual for a lab practical based on current equipment is of crucial importance.

No doubt, virtual labs are becoming more and more popular nowadays. Researches have shown that computer simulated experiments and virtual labs have great potential for improving students' learning outcomes in a Physics practical. However, they will never substitute hands-on experiments. Performing an experiment in practice and finding the results of a specified lab project helps develop the basics for a systematic approach to solve forthcoming real-world technical problems.

Therefore, a significant amount of time and work was put in to bring out this alternative version of teaching materials. It will not only help students studying engineering disciplines to learn the fundamental laws of nature but more importantly engender permanence of knowledge, and problem-solving skills.

We hope that this manual for Physics lab practicals will be helpful and useful for both academic instructors in organizing different programs, and for students of various majors.

Introduction

This manual contains all the necessary theoretical material and description of experimental equipment for preparation to and successful completion of laboratory experiments for foreign students studying in Ukraine.. Some numerical constants are given in appendix to this book.

Each student enrolled in Physics Course must complete this cycle of labs concurrently. In the laboratory, the safety regulations must be strictly followed. Any violation of safety policy or lab manager instructions will result in immediate cancellation of admission to laboratory.

The goal of these labs is to familiarize you with theoretical concepts and experimental techniques. In general, the labs will try to stay in step with the course material; however, in order to benefit of laboratory sessions, it will be necessary to prepare oneself in advance for carrying out an experiment.

Every laboratory manual has one and the same structure. It consists of the experiment's title, objective, list of equipment used, theoretical introduction, derivation of computation formula, description of measurement&analysis procedure, table for experimental results and set of control questions. Experiments are carried out one at a session, attending sessions is mandatory for successful completing the physics course. If for any reason you are unable to attend your assigned lab, you should attend one of the other lab sessions (with other group) during the week, if at all possible. You must inform the instructor beforehand. If you are unable to attend any of the lab sections on a particular week, there will be a make-up session at the end of semester.

Experiments are performed according to rigidly defined methodology, which you will be acquainted with in the introductory sessions. There are strict rules for performing measurements, collecting data, analysing data, estimating experimental errors and presenting final results. Experimental data should be recorded in permanent form. Data should be as complete as possible and should be recorded in ink. Record the data, the precision that it was measured, and note uncertainties. Mistakes are possible, if not probable. Incorrect data entries should not be erased or blotted out, but rather should be crossed out neatly with a fine line. Data should be analyzed as soon as possible after it is recorded. The longer you wait, the easier it is to forget details.

Clearly specify your computation equation or equations. The computation equation(s) has your measured data as the independent variable(s) and your final result(s) as the dependant variable. Log each calculation that transforms your direct measurements into the final quantities in your logbook. That is, make it clear how to start with the data and to arrive at your results. Also trace your calculations of errors as appropriate and as required. The experiment ends with presenting the result in a standerd form, with the numerical value of desired quantity and the mean value of an error specified.

The laboratory experiments are numbered consecutively in each laboratory. The actual number and the order of experiments to be carried out is upon the choice of instructor. The manuals are supplemented with tables of useful data (see Appendices).

Besides this manual we recommend the textbooks:

1. Physics for Scientists and Engineers by Raymond A. Serway.
2. Physics by Yu.M. Nikiforov
3. Fundamentals of Physics by D. Halliday, R. Resnick and J. Walker.

General information on laboratory measurements

Safety measures

In the laboratory of mechanics some instruments can be dangerous in the case of misuse. That is why every student has to know function of each device or appliance used and mode of its application. Otherwise student is not granted a permission to start an experiment. Experiments are carried out under supervision of laboratory assistant.

Students are not allowed to use devices being out of order, to repair devices, to use instrument not according to its function, to take anything out of the lab.

If some part of apparatus or arrangement moves during the experiment, before starting the experiment the experimentalist has to take sure, that every part is safely fastened and threaten nobody. No device should be left without notice during the experiment.

Measurements and Units

A measurement is a numerical rating of a property of a physical system: the height and weight of a character, the speed and acceleration of a vehicle, the energy contained in system, etc. A measurement always consists of two parts: a magnitude and its units. The magnitude indicates "how much," while the units indicate what property is being measured and which standard of measure is being used to rate it; i.e., "How much of what?" For instance, "7 kg" indicates that mass is being measured in pounds, and that it has been found to be 7 kilograms.

Units in Equations and Formulae

A physical quantity, besides numerical value, is also characterized by a unit of measurement (see Appendix 1 for a list of units for basic quantities).

Units are very important, and without them, a measurement is meaningless. A statement can be made about the units appearing in an equation or formula: the units of quantities on either side of an equal sign must always be identical. You cannot equate a quantity measured in meters to one measured in hours! If you encounter a formula that does do this, then there's probably an error in it somewhere; go back and check it. (Scientists often call checking one's math this way "dimensional analysis.")

Likewise, you cannot add or subtract two quantities with unlike units within a formula (e.g., adding distance in meters to speed in m/s); always make sure that the units of all quantities being added together (or subtracted) are the same. This rule applies even when you have different units that measure the same thing; e.g., you cannot add kilograms to grams, even though both measure mass.

Prefixes

When very large or small quantities are being expressed, it is both more efficient and more intuitive to use units of the appropriate size. This is accomplished by preceding the unit name with a prefix that indicates multiplication by the appropriate power of ten; e.g., "9 mm" (9 millimeters) instead of "0.009 m" (0.009 meters). Standard metric prefixes are listed in table 1.1.

Table 1.1 Standard metric prefixes

Multiplier	Factor	Prefix	Symbol
0.000000000000000000000001	10^{-24}	yocto-	y
0.000000000000000000001	10^{-21}	zepto-	z
0.000000000000000001	10^{-18}	atto-	a
0.000000000000001	10^{-15}	femto-	f
0.000000000001	10^{-12}	pico-	p
0.000000001	10^{-9}	nano-	n
0.000001	10^{-6}	micro-	µ
0.001	10^{-3}	milli-	m
0.01	10^{-2}	centi-	c
0.1	10^{-1}	deci-	d
1,000	10^{3}	kilo-	k
1,000,000	10^{6}	mega-	M
1,000,000,000	10^{9}	giga-	G
1,000,000,000,000	10^{12}	tera-	T
1,000,000,000,000,000	10^{15}	peta-	P
1,000,000,000,000,000,000	10^{18}	exa-	E
1,000,000,000,000,000,000,000	10^{21}	zetta-	Z
1,000,000,000,000,000,000,000,000	10^{24}	yotta-	Y

Measurement instrumentation and measurement techniques

In the laboratory of mechanics vernier calipers and micrometers are used.
Vernier caliper has two scales, one with millimeter points (millimeter scale) and another (vernier scale) with points placed slightly closer then a millimeter. The millimeter scale is placed on frame R and the vernier scale is on the mobile frame L. Using vernier caliper one can measure outer dimensions (as shown in figure 1, with parts c and d), inner dimensions (with parts e and f), or depth of cavities (with pole g).

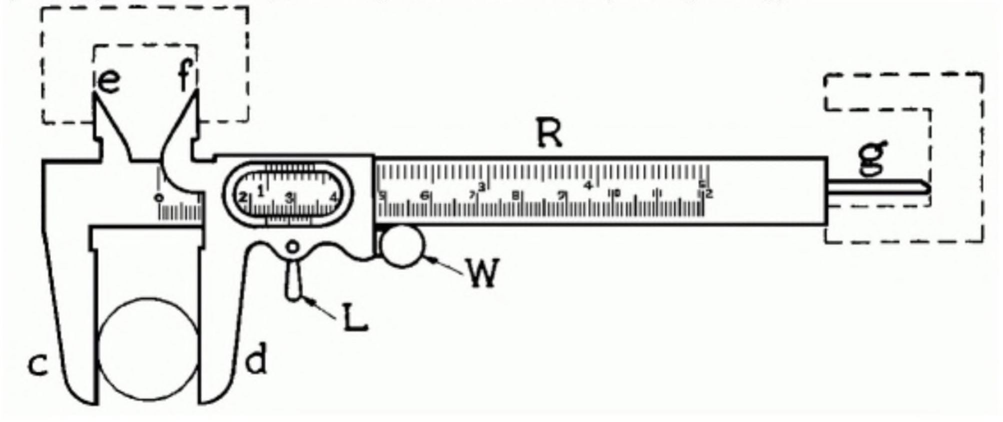


Fig.1 Vernier caliper

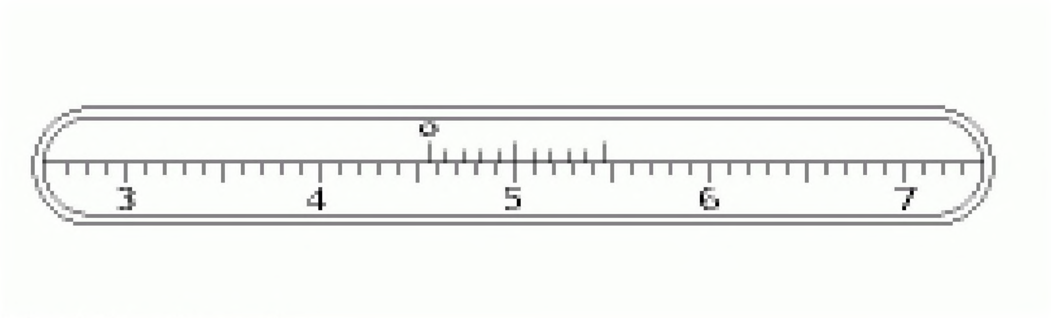


Fig. 2 Vernier scale

The millimeter scale allows to measure lengths with an accuracy of one millimeter in the same way, as drawing scale does. Data from the vernier scale (see fig. 2) allows to rise accuracy of measurement by an order of magnitude. Note, that in initial state (before the measurement) the tenths point of vernier scale matches with the ninth point of millimeter scale (upper part of fig.3). If during the measurement the mobile frame of caliper is shifted so as the eights point of vernier matches some (no matter which) point of millimeter scale as shown by an arrow in lower part of fig.3, we have to add eight tenths of millimeter to the data read from millimeter scale. If we read for example, 4 mm from the millimeter scale, and 0.8 mm from vernier, the overall length of measured object is 4 mm + 0.8 mm = 4.8 mm.

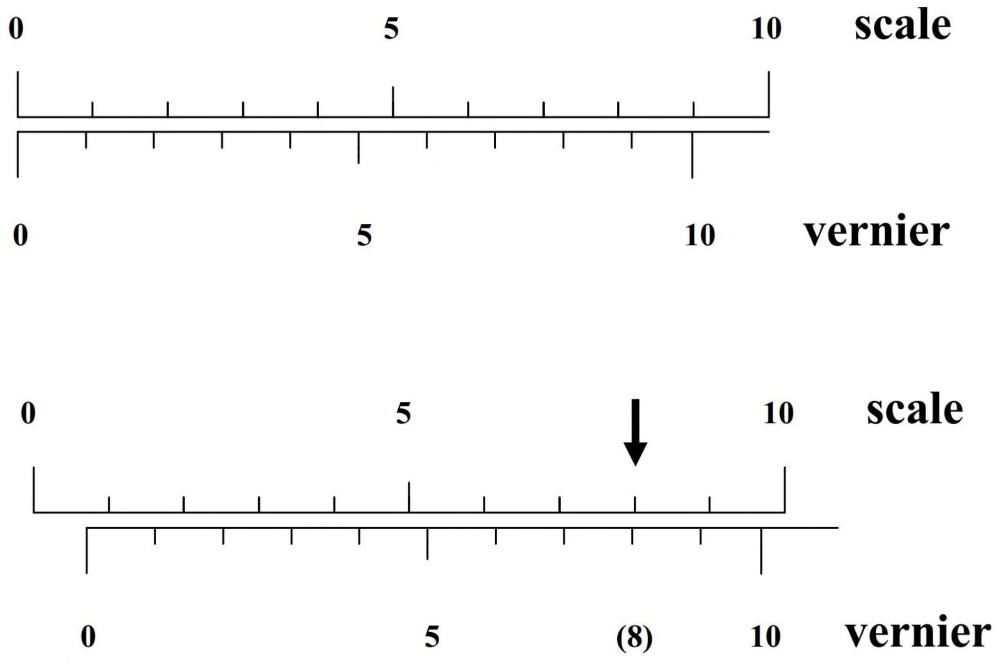


Fig. 3 Measuring with vernier scale

Way of measurement by the micrometer (fig.4) is very similar to caliper. Micrometer is provided with two scales also, millimeter scale S on its body and vernier scale on mobile barrel T. Holding the part F by left hand one can rotate the knob H of the micrometer by right hand, thus moving rod R closer to rod A. If the measured body is already clutched by these two rods, one can read data from the millimeter scale S first, then from vernier scale (in hundredths of a millimeter) and, finally, add these data to obtain the overall result.

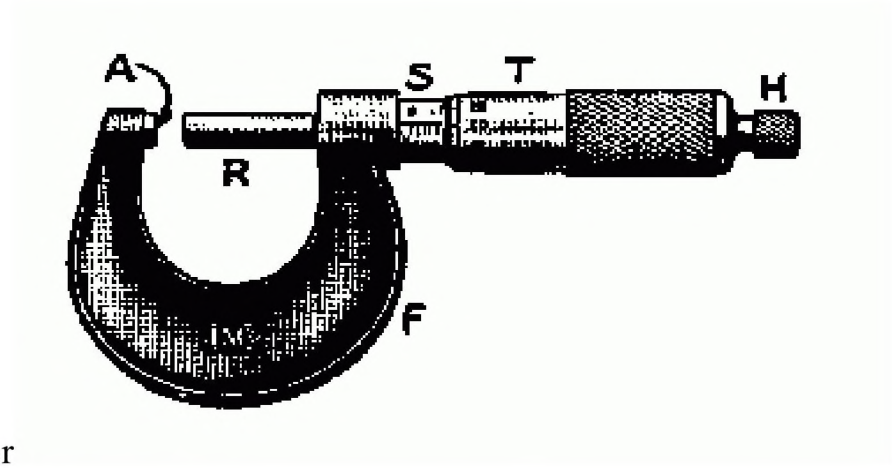


Fig. 4. Micrometer

One should note, that while the instrumental error of a drawing scale is equal one half of the distance between next nearest points of it, the errors of vernier calipers and micrometers are 0.1 mm and 0.01mm, respectively (unless other value is specified on the body of the instrument).

Stop-watches are used in the lab for measurements of time intervals. As a rule, stop watches have two scales on display, one for seconds and another for hundredths of a second. At the end of the measured time interval one stops measurement by pressing the knob or button and then add data from the seconds scale and the hundredths scale. If the watch is started and stopped manually, its error is always taken to be equal to 0.2 s, because of human's time of reaction. If the measurement if fully automated (e.g., starting and stopping by photogates) the instrumental error is equal to one half of the last known digit.

Measurement errors. Methods of error estimation.

No measurement is perfectly accurate or exact. Many instrumental, physical and human limitations cause measurements to deviate from the "true" values of the quantities being measured. These deviations are called "experimental uncertainties," but more commonly the shorter word "error" is used.
What is the "true value" of a measured quantity? We can think of it as the value we'd measure if we somehow eliminated all error from instruments and procedure. We can improve the measurement process, of course, but since we can never eliminate measurement errors entirely, we can never hope to measure true values. We have only introduced the concept of true value for purposes of discussion. When we specify the "error" in a quantity or result, we give an estimate of how much that measurement is likely to deviate from the true value of the quantity. This estimate is far more than a guess, for it is founded on a physical analysis of the measurement process and a mathematical analysis of the equations which apply to the instruments and to the physical process being studied.

Error analysis is an essential part of the experimental process. It allows us to make meaningful quantitative estimates of the reliability of results.

Experimental errors are of two types: (1) indeterminate and (2) determinate (or systematic) errors.

1. Indeterminate Errors.

Indeterminate errors are present in all experimental measurements. The name "indeterminate" indicates that there's no way to determine the size or sign of the error in any individual measurement. Indeterminate errors cause a measuring process to give different values when that measurement is repeated many times (assuming all other conditions are held constant to the best of the experimenter's ability). Indeterminate errors can have many causes, including operator errors or biases, fluctuating experimental conditions, varying environmental conditions and inherent variability of measuring instruments.

The effect that indeterminate errors have on results can be somewhat reduced by taking repeated measurements then calculating their average. The average is generally considered to be a "better" representation of the "true value" than any single measurement, because errors of positive and negative sign tend to compensate each other in the averaging process.

2. Determinate (or Systematic) Errors.

The terms *determinate error* and *systematic error* are synonyms. "Systematic" means that when the measurement of a quantity is repeated several times, the error has the *same size and algebraic sign* for every measurement. "Determinate" means that the size *and sign* of the errors are determinable (if the determinate error is recognized and identified).

A common cause of determinate error is instrumental or procedural *bias*. For example: a miscalibrated scale or instrument, a color-blind observer matching colors.

Another cause is an outright experimental blunder. **Examples:** using an incorrect value of a constant in the equations, using the wrong units, reading a scale incorrectly.

Every effort should be made to minimize the possibility of these errors, by careful calibration of the apparatus and by use of the best possible measurement techniques.

Determinate errors can be more serious than indeterminate errors for three reasons. (1) There is no sure method for discovering and identifying them just by looking at the experimental data. (2) Their effects can *not* be reduced by averaging repeated measurements. (3) A determinate error has the same size and sign for each measurement in a set of repeated measurements, so there is no opportunity for positive and negative errors to offset each other.

Indeterminate errors

Indeterminate errors are "random" in size and sign. The origin of indeterminate errors lies in the probabilistic nature of the measurement process, in imperfectness of measured bodies and human senses, changes in enviroment, in all factors, which we are unable to control.

Consider again the data set which may have been obtained in a series of measurements

3.69 3.68 3.67 3.69 3.68 3.69 3.66 3.67

We'd like an estimate of the "true" value of this measurement, the value which is somewhat obscured by randomness in the measurement process. Common sense suggests that the "true" value probably lies somewhere between the extreme values 3.66 and 3.69, though it *is* possible that if we took more data we might find a value outside this range.

From this set we might quote the arithmetic mean (average) of the measurements as the best value. Then we could specify a maximum range of variation from that average:

3.68 ± 0.02

This is a standard way to express data and results. The first number is the experimenter's best estimate of the true value. The last number is a measure of the "maximum error."

When the experimental data with known errors are substituted into computation formula to yield a final result, the error of the final result may be estimated using rules summarized in table 1.2

Table 1.2 Rules for elementary operations (*indeterminate* errors)

	Computation formula	Indeterminate error	
		Absolute (Δy)	Relative $\left(\frac{\Delta y}{y}\right)$
1.	$y=x_1+x_2$	$(\Delta x_1+\Delta x_2)$	$\frac{\Delta x_1+\Delta x_2}{x_1+x_2}$
2.	$y=x_1-x_2$	$(\Delta x_1+\Delta x_2)$	$\frac{\Delta x_1+\Delta x_2}{x_1-x_2}$
3.	$y=x_1\cdot x_2$	$(x_1\Delta x_2+x_2\Delta x_1)$	$\left(\frac{\Delta x_1}{x_1}+\frac{\Delta x_2}{x_2}\right)$
4.	$y=x^n$	$nx^{n-1}\Delta x$	$n\frac{\Delta x}{x}$
5.	$y=e^x$	$e^x\Delta x$	Δx
6.	$y=\ln x$	$\frac{\Delta x}{x}$	$\frac{\Delta x}{x\ln x}$
7.	$y=\frac{x_1}{x_2}$	$\left(\frac{x_1\Delta x_2+x_2\Delta x}{x_2^2}\;{}_1\right)$	$\left(\frac{\Delta x_1}{x_1}+\frac{\Delta x_2}{x_2}\right)$
8.	$y=\sin x$	$(\cos x)\Delta x$	$(\mathrm{ctg}\, x)\Delta x$
9.	$y=\cos x$	$(\sin x)\Delta x$	$(\tan x)\Delta x$

Precision and accuracy

A measurement with relatively small indeterminate error is said to have high precision. A measurement with small indeterminate error *and* small determinate error is said to have high *accuracy*. *Precision* is the degree of certainty with which you know a number. Precision does not necessarily imply accuracy. A precise measurement may be inaccurate if it has a determinate error.

An *exact* quantity is just that - there is no doubt as to what the quantity is, you are completely certain of it. Virtually all other quantities are expressed as decimals, and therefore have a finite precision. Generally speaking, the more decimals places you show, the more precise the number. For instance, "0.12000" implies more precision than "0.12." However, only indicate precision that is really there. If you round 0.11999 to 0.12 (see *Rounding Conventions,* below), then you *have* to write "0.12," because "0.12000" would imply the number is known to be 0.12000 to five decimal places, and since it isn't (it's 0.11999 to five places), this would be incorrect. Likewise, if you round to 0.120, then you have to write "0.120" and if you round to 0.1200, then you must write "0.1200." In no case would "0.12000" be correct for 0.11999.

Importance of repeated measurements

A single measurement of a quantity is not sufficient to convey any information about the quality of the measurement. You may need to take repeated measurements to find out how consistent the measurements are.

If you have previously made this type of measurement, with the same instrument, and have determined the uncertainty of that particular measuring instrument and process, you may appeal to your experience to estimate the uncertainty. In some cases you may know, from past experience, that the measurement is *scale limited*, that is, that its uncertainty is smaller than the smallest increment you can read on the instrument scale. Such a measurement will give the same value exactly for repeated measurements of the same quantity. If you know (from direct experience) that the measurement is scale limited, then quote its uncertainty as the smallest increment you can read on the scale.

Students in this course don't need to become experts in the fine details of statistical theory. But they should be constantly aware of the experimental errors and do whatever is necessary to find out how much they affect results. Care should be taken to minimize errors. The sizes of experimental errors in both data and results should be determined, whenever possible, and quantified by expressing them as average deviations.

Rounding numbers. Representing experimental results.

When physical quantities are measured, the measured values are known only to within the limits of the experimental uncertainty. The value of this uncertainty can depend on various factors, such as the quality of the apparatus, the skill of the experimenter, and the number of measurements performed.

Suppose that we are asked to measure the area of a computer disk label using a meter stick as a measuring instrument. Let us assume that the accuracy to which we can measure with this stick is 0.1 cm. If the length of the label is measured to be 5.5 cm, we can claim only that its length lies somewhere between 5.4 cm and 5.6 cm. In this case, we say that the measured value has two significant figures. Likewise, if the label's width is measured to be 6.4 cm, the actual value lies between 6.3 cm and 6.5 cm. Note that the significant figures include the first estimated digit. Thus we could write the measured values as (5.5 ± 0.1) cm and (6.4 ± 0.1) cm.

In general, a significant figure is a reliably known digit (other than a zero used to locate the decimal point). For addition and subtraction, you must consider the number of decimal places when you are determining how many significant figures to report. For example, if we wish to compute 123 + 5.35, the answer given to the correct number of significant figures is 128 and not 128.35.

Scientific Notation

This is an extension of the decimal system for really large or small numbers. The number is expressed as a decimal fraction multiplied by an appropriate power of 10. This is only really useful for numbers with lots of zeroes in them, in which case it can be a major space-saver. For instance, 1,200,000,000 is really just 1.2 times 1,000,000,000, and 1,000,000,000 is just 10^9, so one could write this as 1.2×10^9.

Rounding Conventions

When doing calculations, one often ends up with long decimal numbers. As per the guidelines above, these must be rounded off to the appropriate number of significant figures. Note that in a long, complex calculation, you only do this *once, at the end of the calculation,* not at each step along the way.

The rules for rounding, called *rounding conventions,* are as follows: When rounding off a number, look at the digit one place beyond the place you are rounding off to. If this digit is 0, then simply drop the 0; e.g., 56.70 becomes 56.7. If this digit is between 1 and 4, round the number *down;* e.g., 56.73 becomes 56.7 (and not 56.8). If this digit is between 5 and 9, then round the number *up;* e.g., 56.77 becomes 56.8 (and not 56.7).

Reporting results.

The standard form for measured values and results is: (value) ± (est. error in the value),

for example: 3.68 ± 0.02 seconds.

The proper style for scientific notation is: $(6.35 \pm 0.003) \times 10^6$.

Remember that in giving your final answer you must give the proper number of significant figures.

Experiment M1

STUDY OF TRANSLATIONAL MOTION LAWS WITH ATWOOD MACHINE

Objective of the experiment: Study of the translation motion laws for a rigid body. Determination of translation motion acceleration.

1 EQUIPMENT

1. Experimental apparatus (Atwood machine).
2. Two identical weights bound together by a cord.
3. Set of different mass rings.

2 THEORY

2.1 There are three approaches, equally appropriate for description of a particle (point-like object) motion. These are trajectory, position-vector and coordinates approaches. The trajectory approach is the most convenient one, if a trajectory is known. Trajectory is a line, along which the point moves. In the position vector (radius-vector) approach, the position of a point at every moment is determined by a vector $\vec{r}$, whose beginning is superposed with the origin of reference frame chosen and end is superposed with the point. One obtains a coordinate description by decomposition of position vector in three coordinate components, each being a vector directed along one of the coordinate axes:

$$\vec{r} = x\vec{i} + y\vec{j} + z\vec{k}, \tag{2.1}$$

where x, y, z are projections of position-vector $\vec{r}$ on the respective coordinate axes of Cartesian coordinate system; $\vec{i}$, $\vec{j}$ and $\vec{k}$ are unit vectors directed along the respective axes.

2.2 Instantaneous velocity of a particle may be defined as

$$\vec{\vartheta} = \frac{d\vec{r}}{dt} = \vartheta_x\vec{i} + \vartheta_y\vec{j} + \vartheta_z\vec{k}, \tag{2.2}$$

where ϑ_x, ϑ_y, ϑ_z are the projections of velocity vector $\vec{\vartheta}$ on coordinate axes:

$$\vartheta_x = \frac{dx}{dt}, \quad \vartheta_y = \frac{dy}{dt}, \quad \vartheta_z = \frac{dz}{dt}. \tag{2.3}$$

The unit of velocity in metric system is one meter per second, 1 $\frac{m}{s}$. The velocity of a body's motion with respect to inertial frame of reference can be changed under the external influences (forces exerted on the body). This change is characterized by an acceleration, which is defined as time rate of velocity change:

$$\vec{a} = \frac{d\vec{\vartheta}}{dt} = a_x\vec{i} + a_y\vec{j} + a_z\vec{k}, \tag{2.4}$$

here, a_x, a_y, a_z are projections of the acceleration vector on coordinate axes:

$$a_x = \frac{d\vartheta_x}{dt}, \quad a_y = \frac{d\vartheta_y}{dt}, \quad a_z = \frac{d\vartheta_z}{dt}. \tag{2.5}$$

The unit of acceleration in metric system is one meter per second square, 1 $\frac{m}{s^2}$.

2.3 Let us consider kinematic relations for uniform and accelerated motions.

Uniform motion is a motion with constant velocity.

If motion is rectilinear (one-dimensional), it is convenient to take advantage of coordinate description and direct the OX -axis along the direction of body's motion):

$$\vartheta_x = \frac{dx}{dt}, \qquad a_x = \frac{d\vartheta_x}{dt}, \tag{2.6}$$

all other components of velocity and acceleration equal zero. As $\vartheta_x = const$ at uniform motion, from the latter equation we immediately obtain $a_x = 0$, and integration of the equations (2.6) with respect to time gives

$$x = x_0 + \vartheta_x t, \tag{2.7}$$

where x denotes the position of moving particle at the moment of time t, and x_0 denotes the position of particle at the initial moment ($t=0$).

Uniformly accelerated motion (acceleration is constant $a_x = const$).

If a motion is one-dimensional (along OX -axis), we have $a_x = \text{const}$, successive integration of formulas (2.6) provides us with the expressions for the particle velocity as a function of time

$$\vartheta_x = \vartheta_{0x} + a_x t, \tag{2.8}$$

and the particle position as a function of time

$$x = x_0 + \vartheta_{0x} t + \frac{a_x t^2}{2}; \tag{2.9}$$

here x_0 stands for initial position of the particle (at the moment $t=0$), ϑ_{0x} denotes initial velocity along OX -axis. These equations constitute the system of kinematic equations for accelerated motion.

The value of velocity increases in magnitude if projections ϑ_x and a_x have the same sign, and vice versa.

2.4 Dynamics studies the laws of mechanical motion by revealing the causes of this motion.

In dynamics the notions of force and mass are fundamental. Interaction of bodies may cause either deformation of body or acceleration of it. Force is the measure of this interaction. Force is a quantity, which is characterized by the point of application, a magnitude and a direction of the action (therefore, force is a vector). If a few forces $\vec{F}_1$, $\vec{F}_2$, ... $\vec{F}_n$ are exerted on a body at the same time, a net force $\vec{F}$ is found by the superposition principle: $\vec{F} = \vec{F}_1 + \vec{F}_2 + \ldots + \vec{F}_n$.

Inert mass is the measure of a body's inertia. Inert mass m quantitatively characterizes the matter, which a body consists of. Inertia means the property of a matter to resist the change of the state of motion.

Three laws formulated by Isaac Newton are fundamental in dynamics.

The first Newton's law is: there are reference frames (inertial RF) in which a body remains in rest or uniform translational motion if no external force act on it or external forces balance each other. This law is called the law of inertia as well.

In the inertial frames of reference at velocities ϑ, considerably less than velocity of light ($\vartheta^2 << c^2$) the second Newton's law takes place:

$$\vec{F} = m\vec{a} \qquad \text{or} \qquad \vec{a} = \frac{\vec{F}}{m} \tag{2.10}$$

that is, acceleration a body moves with, is proportional to resultant of all forces, exerted on the body, and inversely proportional to mass of the body.

Equation (2.10) sets up a definition for unit of force, newton (N): 1 N is the force which provides the body of 1 kg mass with acceleration of 1 m/s^2 (1 N = 1 kg·m/s^2).

The third Newton's law: If a body A acts on a body B with force $\vec{F}_1$, then body B acts on a body A with force $\vec{F}_2$, these forces being equal in magnitude and opposite in direction:

$$\vec{F}_1 = -\vec{F}_2. \tag{2.11}$$

The third Newton's law states the equality of action and counteraction.

2.5 The simplest motions of a rigid body are translational motion and rotational motion around a fixed axis. In translational motion all points of a body move with identical velocities and accelerations along identical trajectories. Any line, that passes through a body, moves parallel to itself. In rotational motion of a rigid body around fixed axis all points of the body move on circular trajectories, the centers lying on the same line called the rotation axis. Circles, the points of body move on, lie in the planes perpendicular to the axis of rotation. Points of the body, lying on the rotation axis are immobile.

At translational motion velocities and accelerations are the same for all points of a rigid body, so the kinematic relations, derived for a particle, can be applied to describe the motion of body's center of mass. The mass center of the system of bodies moves as a particle with mass, equal to the total mass of the system, to which the net force is applied. Net force is equal to the vector sum of all acting forces.

3 DESCRIPTION OF EXPERIMENTAL APPARATUS

The experimental apparatus (Fig. 3.1), known as Atwood machine, consists of pulley B, over which two identical weights C and C′ with masses m bound together by a cord are suspended. The pulley B is mounted on a stand A provided with a millimeter scale. On the stand an immobile bracket E with an electromagnet and mobile brackets F and G with built-in photogates are mounted, too. If ring D of mass m_1 is placed onto the weight C, the bound weights start accelerated motion. An electronic block is turned on by pressing the "ON/OFF" button. In an initial state electromagnet E holds the weight C′ in the lowest position. The ring D should be placed onto the weight C. The reading of electronic block should then be cleared off by pressing the "CLEAR" button. To start an experiment, the button "START" is to be pressed, then an electromagnet is turned off and the weights motion starts. The weight C moves with constant acceleration from its upper position to the bracket F. The ring D being taken off from the weight C by the bracket F, the weights C and C′ move uniformly. The photogates start

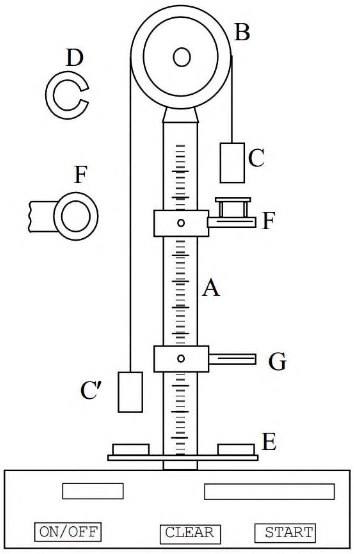


Figure 3.1

measuring the time at the moment when the weight C is passing the bracket F and stop the measurement when the bracket G is reached. From the display of the electronic block the time of uniform motion between points F and G can be read from. Distance between these brackets is measured by the millimeter scale on the stand.

4 DERIVATION OF COMPUTATION FORMULAS

4.1 In order to derive the system acceleration one may apply the system of kinematic equations for accelerated motion. Initial velocity of the weights equals zero. In time interval t_1 the weight C, moving with acceleration, passes the path

$$S_1 = \frac{a_1 \cdot t_1^2}{2}, \tag{4.1}$$

its speed reaches the value

$$\vartheta = a_1 \cdot t_1. \tag{4.2}$$

After the ring D is taken off while passing the bracket F, gravity force and tension of the string cancel each other, so the net force is zero and the motion of weight C becomes uniform. Moving with constant velocity ϑ, the weight C covers a distance

$$S_2 = \vartheta \cdot t_2 \tag{4.3}$$

in time t_2.

From equations (4.1)-(4.3) we obtain the for the acceleration:

$$a_1 = \frac{S_2^2}{2S_1 t_2^2}. \tag{4.5}$$

4.2 Acceleration of the system can be determined using the laws of dynamics as well.

The weight C is under the actions of the gravitation field of Earth, the cord it is suspended on, the ring D and surrounding air (see Fig. 4.1). Neglecting the friction in air, the second law of Newton for the weight C can be written down as follows:

$$m\vec{g} + \vec{P} + \vec{T}_1 = m\vec{a}_1, \tag{4.6}$$

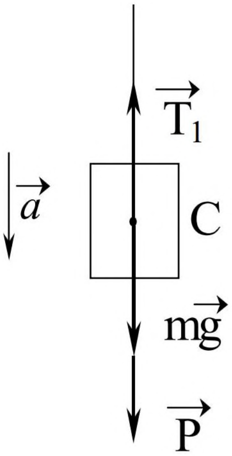


Figure 4.1

where m is the mass of the weight C, $\vec{g}$ is a free fall acceleration, $\vec{P}$ is the force, exerted by the ring D on the weight C, $\vec{T}_1$ is tension force of the string. Projecting equation (4.6) on the vertical axis we obtain:

$$T_1 - mg - P = -ma_1. \tag{4.7}$$

Analogously, one obtains the equation of motion for the weight C′:

$$T_2 - mg = ma_2, \tag{4.8}$$

and the equation of motion for the ring D:

$$N - m_1 g = -m_1 a_1, \tag{4.9}$$

here N stands for a magnitude of the reaction force, acting on the ring D from the weight C. It follows from the third Newton's law that $N=P$. As the cord is considered to be untensile, acceleration magnitudes for all the weights are equal $a_1 = a_2 = a$. The cord tension forces can be considered equal only if the pulley moment of inertia may be neglected and a friction is absent. If mass of the pulley and a friction are neglected, then $T_1=T_2=T$. From equations (4.7)-(4.9) one may obtain the expression for the acceleration:

$$a = \frac{m_1}{2m + m_1} g \,. \qquad (4.10)$$

Expressions (4.5) and (4.10) are the computation formulas of the experiment.

5 PROCEDURE AND ANALYSIS

5.1 Mount brackets G and F on a distance S_2 specified by laboratory assistant
5.2 Put the weight C′ in the lowest position. Turn on an electronic block. Place the ring D onto the weight C (weight of ring D is specified by lab assistant).
5.3 Note initial position of the weight C on a millimeter scale and determine the distance S_1.
5.4 Press the button “START” to put the system in motion and measure time t_2.
5.5 Repeat the experiment two times more. Determine the average values of S_1 and t_2.
5.6 Calculate acceleration using formula (4.5).
5.7 Determine masses of the weights used.
5.8 Calculate acceleration using formula (4.10).
5.9 Compare the values of the acceleration calculated using formulas (4.5) and (4.10).
5.10 Estimate errors of measurements and calculations.
5.11 Express results of the calculation in a form $a = a_m \pm \Delta a_m$ and specify the value of relative error ε.
5.12 Fill the tables 5.1 and 5.2 with results of experiments and calculations.

Table 5.1

N	S_1 10^{-3} m	ΔS_1 10^{-3} m	S_2 10^{-3} m	ΔS_2 10^{-3} m	t_2 s	Δt_2 s	a, m/s^2	Δa m/s^2	ε %
1			▨	▨			▨	▨	▨
2									
3									
Mean value									

Table 5.2

m 10^{-3} kg	Δm 10^{-3} kg	m_1 10^{-3} kg	Δm_1 10^{-3} kg	g m/s^2	Δg m/s^2	a, m/s^2	Δa m/s^2	ε %

6 CONTROL QUESTIONS

6.1 What is translational motion?
6.2 What is velocity? What types of velocity do you know? Write down equation for velocity determination.
6.3 What is acceleration? What is unit of acceleration in SI?
6.4 What is force? What is unit of force in SI? How the net force is calculated?
6.5 Formulate Newton’s laws.

Experiment M2

DETERMINATION OF LIQUID VISCOSITY BY STOCKES METHOD

Objective of the experiment: To master the basic concepts of fluid mechanics and to determine the dynamic coefficient of viscosity for a liquid.

1 EQUIPMENT

1. Stockes' apparatus.
2. Metallic ball.
3. Micrometer.
4. Vernier caliper.
5. Stop-watch.

2 THEORY

2.1 In many practically important cases, the fluid mechanics based on the notion of an ideal liquid is not applicable. In distinction from the ideal liquid, in real ones there exist the forces tangential to the surface of moving layers contact. These forces are called viscous friction (internal friction) forces or viscous forces.

Viscosity is the property of a fluid (liquid or dense gas) to offer resistance at the relative motion of their layers.

2.2 In the stream of the real liquid in the close vicinity of solids, moistened by it, the layers move with different velocities. The layer which touches a solid directly has zero velocity. The further a layer is from the resting solid, the larger is the value of its velocity.

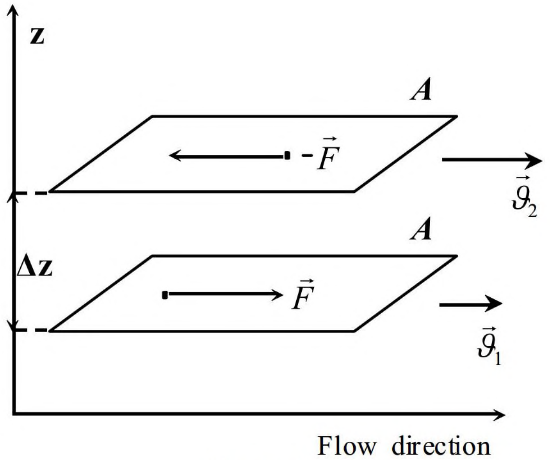


Figure 2.1

Let us imagine the stream of liquid to be composed of infinitely many layers. Friction forces appear when the layers start moving relatively to each other. Let us choose two parallel layers in a stream of liquid with equal areas A (see Fig. 2.1). Let Δz denote the distance between the layers. Experiments show that tangent friction forces act on every layer, the force acting on the layer, which moves slower, is directed along the velocity and that acting on the faster layer is opposite to the velocity. The magnitude of this viscous force is given by the law of Newton

$$F = \eta A \left| \frac{\Delta \vartheta}{\Delta z} \right|, \tag{2.1}$$

where η denotes the coefficient of dynamic viscosity (or coefficient of internal friction); A is the area of layer surface; $\left|\frac{\Delta\vartheta}{\Delta z}\right|$ is the rate of velocity change in the direction, perpendicular to the flow direction.

2.3 Using equation (2.1), we have

$$\eta = \frac{F}{\left|\frac{\Delta\vartheta}{\Delta z}\right| A}. \tag{2.2}$$

The coefficient of dynamic viscosity is quantitatively equal to force of friction, that acts on unit of layer surface, if change of speed in perpendicular direction is equal to 1m/s on 1 m of distance. In the SI system of units the viscosity is measured in Pa·s

$$[\eta] = \frac{1\,\mathrm{N}}{\frac{1\frac{\mathrm{m}}{\mathrm{s}}}{1\,\mathrm{m}} \cdot 1\,\mathrm{m}^2} = 1\frac{\mathrm{N}\cdot\mathrm{s}}{\mathrm{m}^2} = 1\mathrm{Pa}\cdot\mathrm{s}.$$

Viscosity of liquids strongly depends on temperature. At the rise of temperature the viscosity coefficient decreases.

2.4 Let us consider motion of symmetric body in the real liquid. As a result of viscosity the liquid can not slide freely along the surface of body, very thin layer of liquid covers the surface of body and moves with it as a whole. Therefore, there are forces of friction only between the layers of liquid, not between the solid and the liquid, so these forces does not depend on material of the body and are determined only by body's shape and properties of liquid.

Experiments show that the value of resulting force of viscosity, exerted on a body, is proportional to the value of body's velocity (if value of velocity is small enough)

$$F = C\vartheta. \tag{2.3}$$

The coefficient of proportionality C depends on the shape of body, its characteristic dimensions, orientation in the stream of liquid and properties of the liquid.

In front of the moving body the pressure of fluid is larger than one behind the body, so the force acts on the body in opposite direction to its velocity. The value of this drag force equals

$$F_{drag} = C_1\vartheta^2. \tag{2.4}$$

Here C_1 is a coefficient of proportionality, which also depends on the body's shape, its characteristic dimensions, orientation in the stream of liquid and properties of the liquid.

Consequently, both viscous friction force and drag force act simultaneously on a symmetric body in the stream. Forces of viscous friction are applied to lateral surface of body, drag forces are applied to the fore-part of the body, it depends on speed of the specific stream, which forces have larger influence. In this experiment relative velocities are small, so grad forces may be neglected.

3 DERIVATION OF COMPUTATION FORMULA

One of methods for determination of dynamic viscosity coefficient η is Stockes' method, based on measuring of speed of uniform motion of small spherical body (ball) in the liquid under investigation.

In the case of small speed (when a flow is laminar one) the force of viscous friction F (by Stockes' law, see formula 2.3) is proportional to the coefficient of viscosity, radius of the ball r and velocity of the ball ϑ

$$F = 6\pi\eta r\vartheta . \tag{3.1}$$

Let us consider the falling of ball in a stationary liquid. Three forces are applied to the falling ball (Figure 3.1), namely the gravity force, upward buoyant (Archimedes') force $\vec{F}_A$ and the force of viscous (internal) friction $\vec{F}$, directed against motion of the ball. At first the ball moves with constant acceleration, however with the increase of speed force of viscous friction increases and reaches a value large enough to balance all other acting forces (see Figure 3.1)

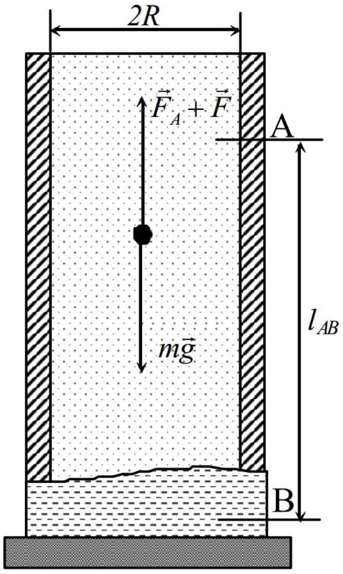


Figure 3.1

$$mg = F + F_A . \tag{3.2}$$

The buoyant force is given by expression:

$$F_A = m_L g = V\rho_L g = \frac{4}{3}\pi r^3 \rho_L g , \tag{3.3}$$

where m_L is mass of liquid in the volume of the ball; ρ_L is density of the liquid; V is volume of the ball; g stands for the free fall acceleration.

Gravity force for the ball can be written as

$$m_b g = V\rho_b g = \frac{4}{3}\pi r^3 \rho_b g , \tag{3.4}$$

where ρ_b denotes density of the body. Taking into account expressions for forces (3.1), (3.3) and (3.4) in formula (3.2), we get

$$\frac{4}{3}\pi r^3 \rho_b g = 6\pi r\eta\vartheta + \frac{4}{3}\pi r^3 \rho_L g , \tag{3.5}$$

from where we obtain for the coefficient of dynamic viscosity

$$\eta = \frac{2}{9}\frac{r^2(\rho_b - \rho_L)g}{\vartheta} \tag{3.6}$$

Stockes' law (3.1) and formula (3.6) are valid in the case, when a body moves uniformly, without the rotation or turbulence, in a homogeneous liquid which has no bounds.

In this experiment the ball falls in a long cylinder with an internal radius R. Taking into account finite dimensions of the cylinder we have to rewrite formula (3.6) as

$$\eta = \frac{2}{9}\frac{r^2(\rho_b - \rho_L)g}{\vartheta(1 + 2{,}4\frac{r}{R})} . \tag{3.7}$$

Apparatus to be used for determination of viscosity coefficient is composed by of the long cylinder filled with a liquid. There are two marks on the cylinder, A and B (Figure 3.1). An overhead mark is made on such a distance from the upper level of liquid, that a ball having passed this distance moves uniformly. The distance l_{AB} between marks A that B is passed with the constant velocity

$$\vartheta = \frac{l_{AB}}{t} , \tag{3.8}$$

where t is the time of body's sinking from one mark to the other.

Substituting (3.6) in (3.5) and taking into account, that in experiment not radii but the diameter of the ball d and internal diameter D of the cylinder will be measured, we get a computation formula

$$\eta = \frac{1}{18}\frac{d^2(\rho_b - \rho_L)gt}{l_{AB}(1+2{,}4\frac{d}{D})}. \tag{3.9}$$

4 PROCEDURE AND ANALYSIS

4.1 Using micrometer measure the diameter of the ball d 3 times and calculate its average value.
4.2 Using Vernier caliper measure the internal diameter of glass tube D.
4.3 Using Vernier caliper measure distance l_{AB} between marks on a tube.
4.4 Put the ball into the liquid. Start measuring time by stop-watch at the moment when the ball is passing by the mark A. Stop the measurement when the ball is passing mark B. Determine the time of the falling.
4.5 Take density of the body ρ_b and the liquid ρ_L from the tables.
4.6 Calculate the value of dynamic coefficient of viscosity by formula (3.9).
4.7 Express results of the calculation of a form $\eta = \eta_m \pm \Delta\eta_m$ and specify the value of relative error ε.
4.8 Fill the table 4.1 with results of experiments and calculations.

Table 4.1

N	d, 10^{-3} m	Δd, 10^{-3} m	ρ_{c}, $10^3\cdot\frac{kg}{m^3}$	$\Delta\rho_{c}$, $10^3\cdot\frac{kg}{m^3}$	ρ_{r}, $10^3\cdot\frac{kg}{m^3}$	$\Delta\rho_{r}$, $10^3\cdot\frac{kg}{m^3}$	t, s	Δt, s	D, 10^{-3} m	ΔD, 10^{-3} m
1			▨	▨	▨	▨	▨	▨		
2										
3										
Mean value										

Continuation of table 4.1

N	l_{AB}, 10^{-2} m	Δl_{AB}, 10^{-2} m	g, m/s^2	η, Pa·s	$\Delta\eta$, Pa·s	ε, %
1	▨	▨	▨	▨	▨	▨
2						
3						
Mean value						

5 CONTROL QUESTIONS

5.1 Formulate the law of Newton for force of viscous friction.

5.2 Explain the physical meaning of viscosity coefficient, specify its units in SI.
5.3 To formulate Stockes' law for force of viscous friction.
5.4 What forces act on a body moving in a liquid? On what conditions the motion of the body in a liquid is uniform?
5.5 Under what conditions formulas (3.1) and (3.6) are valid?

Experiment M3

STUDY OF ROTATIONAL MOTION OF RIGID BODY ON OBERBECK PENDULUM

Purpose of the experiment: to master the basic concepts of kinematics and dynamics of rigid body rotational motion and to determine the moment of inertia for Oberbeck pendulum.

1 EQUIPMENT

1. Oberbeck pendulum.
2. Millimeter scale.
3. Stop-watch.
4. Vernier caliper.

2 THEORY

2.1 In rotational motion of rigid body about the fixed axis all points of the body move on circular trajectories, the centers of which lie on the same line called the rotation axis. Circles, which the points of body move on, lie in planes perpendicular to the axis of rotation. Points of a body, which lie on the axis of rotation are immobile. Fig 2.1 illustrates rotational motion of a cross-piece with weights mounted on it, under the action of tension force of a string. One end of the string is fastened on the pulley of radius *r*, the weight of mass *m* is suspended on the other end. In the figure shown the tension force of the string $\vec{F}$, exerted on the pulley and the force $\vec{T}$, acting on the weight *m* from the side of the string, as well as gravity force $m\vec{g}$.

In rotational motion of rigid body about a fixed axis a position of the body is characterized by angle of rotation *φ*, which is an analog of a path in translational motion. The moving points of a body all have the same angular velocity and angular acceleration.

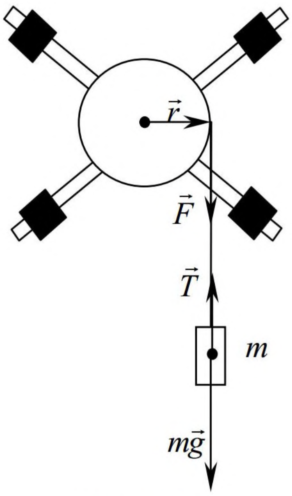


Figure 2.1

We will define the vector of angular velocity $\vec{\omega}$ as

$$\vec{\omega} = \frac{d\varphi}{dt}\vec{k}, \qquad (2.1)$$

where $d\varphi$ is the turn angle made during the time interval *dt*, $\vec{k}$ is a unit vector ($|\vec{k}| = 1$), directed in a positive direction of OZ axis (axis of rotation). By convention, the positive direction is chosen to coincide with the direction of gimlet (drill) motion when its handle is revolved clockwise (this direction is considered positive for angle $d\varphi$). This rule is called the gimlet rule (right hand rule). For the case shown in Fig. 2.1, rods, pulley, weights on the cross-piece, all have the same angular velocity which is directed along the axis of rotation, perpendicular to the plane of the figure. A projection of vector $\vec{\omega}$ on axis OZ equals $\omega = \frac{d\varphi}{dt}$ (magnitude of angular velocity). Unit of angular velocity is 1 rad/s.

Due to the interaction of the body with surrounding bodies the angular velocity of the body can change; this change is characterized by angular acceleration which we will define as

$$\vec{\varepsilon} = \frac{d\omega}{dt}\vec{k} = \frac{d^2\varphi}{dt^2}\vec{k} \tag{2.2}$$

A vector $\vec{\varepsilon}$ has direction of vector $\vec{\omega}$ if magnitude of angular velocity increases ($d|\vec{\omega}|/dt > 0$) and the opposite direction, if ω decreases ($d|\vec{\omega}|/dt < 0$). For the case shown in Fig. 2.1 the direction of angular acceleration of the system coincides with direction of angular velocity. A projection of $\vec{\varepsilon}$ on an axis OZ (magnitude of vector $\vec{\varepsilon}$) equals $\varepsilon = \frac{d\omega}{dt} = \frac{d^2\varphi}{dt^2}$. Unit of angular acceleration is 1 rad/s^2.

Linear kinematic quantities characterizing the specific point of a body (path s, velocity ϑ, tangential acceleration a_τ) are related to the respective angular characteristics by equations

$$s = \varphi \cdot r, \quad \vartheta = \omega \cdot r, \quad a_\tau = \varepsilon \cdot r, \tag{2.3}$$

here(r is radius of a circle, which the given point of body moves on at a given moment.

2.2 Basic concepts of dynamics of rotational motion of a rigid body are moment of inertia and a torque.

2.2.1 Moment of inertia I plays the same role in rotational motion as mass does in translational one. It means that is the moment of inertia is a measure of body's inertia in rotational motion. One can see this from comparison of expression for kinetic energy in rotational motion of a body about a fixed axis ($I\omega^2/2$, where I denotes moment of inertia and ω stands for angular velocity) with expression for kinetic energy in translational motion of a body ($m\vartheta^2/2$).

The moment of inertia of a body of arbitrary geometrical form about some axis can be calculated using following equation

$$I = \sum_i \Delta m_i r_i^2, \tag{2.4}$$

stating that the moment of inertia of a rigid body about an axis equals to the sum of products of elementary masses (material points) and the square of their distances to the axis. If mass is distributed continuously the sum in previous equation evolves into the integral:

$$I = \int r^2 dm = \int r^2 \rho dV, \tag{2.5}$$

where ρ stands for density, dV for elementary volume in the body, r is the distance from the elementary volume dV to the axis of rotation, and the integral is taken over all volume of the body. Unit of moment of inertia is 1 kg·m^2.

One can see that the value of moment of inertia depends on mass of the body, its size, form and the choice of rotation axis. Moment of inertia is additive quantity, that is for the system, that consists of a few bodies, a total moment of inertia equals to the sum of moments of inertia of individual bodies.

From equation (2.5) we obtain, in particular, that the moment of inertia of a particle (material point) about any axis of rotation is:

$$I = mr^2, \tag{2.6}$$

where m is mass of the particle point, r is the distance to the axis of rotation. Using the same formula it is possible to calculate the moment of inertia of body on condition that distance from the axis of rotation to the center of mass is much larger of the characteristic linear dimensions of the body.

Moment of inertia of homogeneous cylinder (disk) about the axis of cylinder is

$$I = \frac{1}{2}mr^2, \tag{2.7}$$

where m is mass of cylinder (disk), r is its radius.

Moment of inertia of a rod about an axis which passes through the center of the rod bar, athwart to it equals

$$I = \frac{1}{12}ml^2, \tag{2.8}$$

where m is mass of the rod, l is its length.

It is possible to determine the moment of inertia experimentally with the help of fundamental law of dynamics of rotational motion of a rigid body.

2.2.2 A body can rotate around a fixed axis on the condition that there is an external force $\vec{F}$ (or a component of a force), in plane perpendicular to the axis, acting on the body. The rotational effect of force $\vec{F}$ is characterized by a physical quantity named torque. A torque in rotational motion plays the same role as force does in translational motion. One may calculate torques about an axis or about a point, these differ in general case.

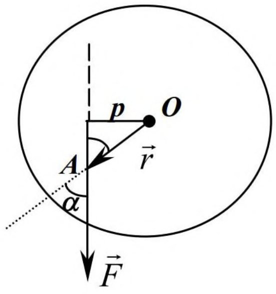


Figure 2.2

We choose the point O on the axis of rotation in the force $\vec{F}$ plane of action (see Fig. 2.2). Then torque of the force $\vec{F}$ with about point O is a vector equal to a cross product of the radius-vector drawn from a point O to the point where the force is applied, and vector of force $\vec{F}$:

$$\tau = \left[\vec{r} \times \vec{F}\right]. \tag{2.9}$$

Module of moment of force:

$$\tau = Fr\sin\alpha = Fp,$$

where α is angle between vectors $\vec{r}$ and $\vec{F}$, and $p = r\sin\alpha$ is the length of the perpendicular dropped from the axis of rotation on the line of action of the force, this perpendicular is called lever arm.

The magnitude of the torque about fixed axis OZ is the projection of torque $\vec{M}$ about the point O onto an axis OZ:

$$\tau_Z = Fr\sin\alpha. \tag{2.10}$$

Torque about the axis, itself, is defined as a vector quantity

$$\tau = \tau_Z \cdot \vec{k},$$

where $\vec{k}$ is the unit vector directed along the axis OZ (the indice z may be omitted).

If there are several forces acting on a body, resulting (net) torque about a point O equals the vector sum of component torques. A magnitude of the torque about an axis is the algebraic sum of projections of component torques.

Unit of a torque is N·m.

2.3 A relation between a torque acting on a body, its angular acceleration and moment of inertia is given by the fundamental law of dynamics of rotational motion (also called the second Newton's law for rotational motion):

$$\tau = I\vec{\varepsilon}\ , \tag{2.11}$$

where τ is net torque. After projecting onto the axis of rotation we have

$$\tau = I\varepsilon\ ,$$

where τ is a magnitude of net torque (algebraic sum of torques), which is the torque projection on the axis of rotation, torque about the axis of rotation.

For the case shown in Fig. 2.1, if we neglect friction forces the magnitude of torque is $\tau = F \cdot r$, the torque is directed along the angular velocity. Having τ and ε given, from formula (2.11) one can find out the moment of inertia of the system composed of cross-piece with weights and the pulley (Fig. 2.1).

3 DESCRIPTION OF EXPERIMENTAL APPARATUS

Below, two experimental apparatus, suitable for the experiment, are described.

A. The main part of Oberbeck pendulum, shown in Fig. 3.1 is composed of a cross-piece (two rods, each of mass m_1 and length l) . The rotation axis of the pendulum pass through the center of cross-piece and center of pulley. On the rods four cylindrical weights of identical mass m_2 are mounted (one can change a distance R from the axis of rotation to the center of a weight on the rod). A string is coiled round the pulley, on the end of string a weight of mass m being suspended.

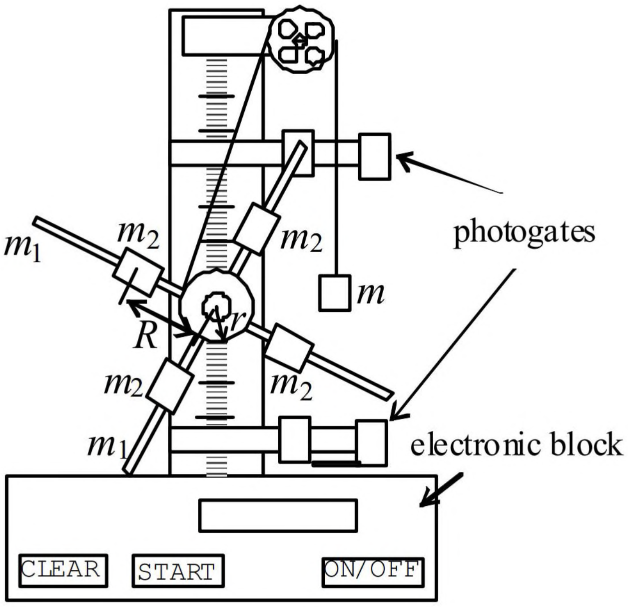


Figure 3.1

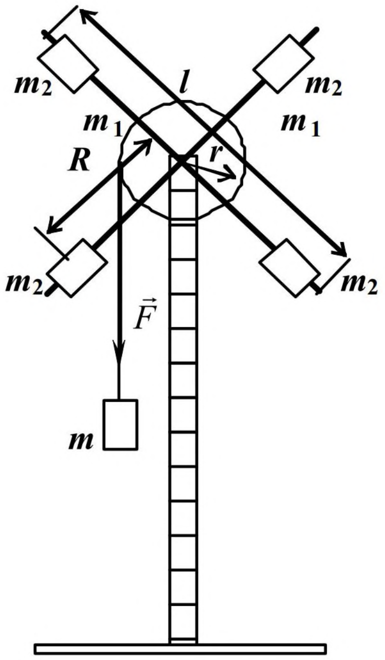


Figure 3.2

Before the beginning of experiment the weight m should be lift in position up, with a string coiled round the pulley, and indications of electronic block should be cleared off by pushing the button "CLEAR". To start an experiment, one pushes the button "START" of an electronic block. Under a tension force of the string the pendulum rotates with an acceleration. When the weight, suspended on a string, passes through an upper photogate, counting the time out begins to be ended when the weight reaches an lower photogate. Distance between photogates (the path of the weight m for time counted by an electronic block) is measured using vertical millimeter scale.

B. Oberbeck pendulum shown in Fig. 3.2 is a cross-piece which consists of two rods, of each of mass m_1, and weights of identical mass m_2, mounted on the rods on distance R from the axis of rotation. The pendulum axis of rotation passes through its center and center of pulley, which a string is coiled round. On the string a weight of mass m is suspended.

Under action of the weight m the coiled string unwinds and a pendulum start to rotate with constant angular acceleration. Position of the weight m is read from a vertical scale.

4 DERIVATION OF COMPUTATION FORMULAS

The moment of inertia of Oberbeck pendulum can be found by two methods. The first is based on application of formula (2.4) to the system under consideration. The second method consists in the use of the fundamental law of dynamics of rotational motion of a rigid body, where quantities τ and ε are expressed through experiment measurables.

The first method.

Being an additive quantity, the moment of inertia of Oberbeck pendulum equals to the sum of moments of inertia of cross-piece, four weights on rods, and pulley. Moment of inertia of cross-piece (two rods) about its center is equal

$$I = \frac{1}{6} m_1 l^2, \tag{4.1}$$

(here we make use of formula (2.8)). Moment of inertia of system of four weights equals

$$I_w = 4 m_2 R^2 \tag{4.2}$$

(a formula (2.6) has been used). Application of formula (2.6) for calculation of total moment of inertia of weights is justifiable when condition $R^2 >> a^2$ is fulfilled (R being the distance from the axis of rotation to the center of masses of the weight, a being linear dimension of weight); in this case the weight can be treated as a particle (material point).

At conditions

$$m_1 + 4m_2 >> m_p, \tag{4.3}$$

$$l >> r, \; R >> r \tag{4.4}$$

(m_p is mass of the pulley), one may neglect the moment of inertia of pulley. Finally, the total moment of inertia equals

$$I = \frac{1}{6} m_1 l^2 + 4 m_2 R^2. \tag{4.5}$$

The second method.

Moment of inertia of pendulum can be found also from the fundamental law of dynamics of rotational motion of a rigid body (2.11).

In this experiment the tension force of string which sets a cross-piece in motion. On the basis of the second law of Newton, at weight descending, this force equals

$$F = mg - ma = m(g - a) \tag{4.6}$$

where g is the free fall acceleration; a is acceleration of suspended weight.

The lever arm of force F is equal to the radius of pulley r, so the torque is

$$\tau = Fr = m(g-a)r. \qquad (4.7)$$

Angular acceleration ε can be calculated if distance h, passed by weight m, and time of descending are known. It is easy to obtain from kinematical equations, that

$$h = at^2/2, \qquad (4.8)$$

therefore

$$a = 2h/t^2. \qquad (4.9)$$

Consequently, as (on a basis of equation (2.3))

$$\varepsilon = a/r, \qquad (4.10)$$

we obtain

$$\varepsilon = 2h/(t^2 r). \qquad (4.11)$$

Substituting equations (4.7), (4.10), (4.11) into formula (2.11), after replacement $r=d/2$ (d is diameter of pulley), we get a computation formula for determination of Oberbeck pendulum moment of inertia:

$$I = \frac{md^2}{4}\left(\frac{gt^2}{2h} - 1\right). \qquad (4.12)$$

5 PROCEDURE AND ANALYSIS

5.1 Determine the masses of weights m, m_1, m_2 and length of rod l.
5.2 Set weights m_2 on rods at distances R from the axis of rotation (value of R is recommended by lab assistant).
Attention: Make sure that weights are safely fastened.
5.3 Calculate the moment of inertia of pendulum using formula (4.5).
5.4 Measure the diameter of pulley by vernier caliper three times in different places and calculate its average value.
5.5 Lift the weight m up on height h (recommended by lab assistant) over the lowest position, reeling string on a pulley.
5.6 Release the weight m and carry out a measurement of its descendence time t.
5.7 Repeat experiment three times and calculate the average value of t.
5.8 Calculate the moment of inertia using formula (4.12).
5.9 Estimate the errors of measurements and calculations.
5.10 Fill the tables 5.1 and 5.2 with results of experiments and calculations.

Table 5.1

m_1, 10^{-3} kg	Δm_1, 10^{-3} kg	l, 10^{-3} m	Δl, 10^{-3} m	m_2, 10^{-3} kg	Δm_2, 10^{-3} kg	R, 10^{-3} m	ΔR, 10^{-3} m	I, 10^{-2} kg·m^2	ΔI, 10^{-2} kg·m^2	ε, %

Table 5.2

N	m, 10^{-3} kg	Δm, 10^{-3} kg	d, 10^{-3} m	Δd, 10^{-3} m	t, s	Δt, s	h, 10^{-3} m	Δh, 10^{-3} m	I, 10^{-2} kg·m^2	ΔI, 10^{-2} kg·m^2	ε, %
1	▨	▨							▨	▨	▨
2											
3											
Mean value											

5.11 Express results of the calculation of a form $I = I_c \pm \Delta I_c$ (for both computation methods) and specify the values of relative errors ε.

6 CONTROL QUESTIONS

6.1 Give definition of a torque and specify its units.
6.2 Give definition of moment of inertia and specify its units.
6.3 Formulate the fundamental law of dynamics of rotational motion of a rigid body.
6.4 Substantiate a statement: the moment of inertia is a measure of inertia of a body at rotational motion.
6.5 In what position of weights on rods the moment of inertia of Oberbeck pendulum would be maximal? Minimal?

Experiment M4

DETERMINATION OF GRAVITY ACCELERATION BY METHOD OF PHYSICAL PENDULUM

Purpose of the experiment: to study oscillations of the physical pendulum; to determine free fall acceleration by method of physical pendulum.

1 EQUIPMENT

1. Physical pendulum.
2. Milimeter scale.
3. Stop-watch.

2 THEORY

2.1 From the law of universal gravitation it follows that on a body lifted above the ground on the height h , the force

$$\frac{\gamma mM}{(R_E + h)^2} = mg, \tag{2.1}$$

is exerted, where a quantity $\vec{g}$ is free fall acceleration, γ=6,67·10^{-11} m^{3}kg^{-1}s^{-2} (Nm^{2}kg^{-2}) is gravitational constant, m is mass of body, M is mass of Earth (M=5,98·10^{24} kg), R_E is the radius of Earth. In a vector form the attractive power can be written down as

$$\vec{F} = m\vec{g}; \tag{2.2}$$

$\vec{F}$ and $\vec{g}$ are directed towards the center of Earth. For a body, that is near to the ground, $h \ll R_Z$ ($R_Z \cong 6{,}37\cdot 10^6$ m)

$$g = \gamma \frac{M}{R_3^2}. \tag{2.3}$$

The value of the free fall acceleration depends on the latitude of a place: on equator it is equal g=9,780 m/s^2, whereas on a pole respective value is g=9,832 m/s^2.

2.2 In this work the value of g is determined in experimental way by method of physical pendulum. Physical pendulum is a body, which oscillates about a horizontal axis hesitates under action of forces, that do not pass through the center of the masses. In the work a rod is used as a physical pendulum (Fig. 3.1).

Sum of kinetic and potential energy of physical pendulum gives the expression

$$E = \frac{I\omega^2}{2} + mgL(1 - cos\,\alpha), \tag{2.4}$$

where I is a moment of inertia of the pendulum, about the axis of rotation which passes through the end of a rod. The specific expression for I may be found using parallel axis theorem. Other values in above equation have the next meaning: ω stands for angular speed of pendulum, m is mass of pendulum, g denotes acceleration of the free fall close to the surface of Earth, L is distance from the axis of rotation to the center of mass, α is a deflection angle of pendulum from equilibrium position. We choose the position of stable equilibrium of pendulum as an origin for potential energy magnitude. After differentiation Eq. (2.4) with respect to time we have

$$I\omega d\omega + mgL\,sin\,\alpha d\alpha = 0\,. \tag{2.5}$$

As $d\alpha = \omega dt$, and angular acceleration is equal to $d\omega / dt = d^2\alpha / dt^2$, instead of Eq. (2.5) we have:

$$I\frac{d^2\alpha}{dt^2} + mgL\,sin\,\alpha = 0\,. \tag{2.6}$$

Let us divide both sides of equation (2.6) on I, introduce notation

$$\omega_0{}^2 = \frac{mgL}{I} \tag{2.7}$$

and consider the case of small deviations from position of equilibrium ($sin\,\alpha \cong \alpha$). Then from Eq. (2.6) we obtain:

$$\frac{d^2\alpha}{dt^2} + \omega_0{}^2\alpha = 0\,. \tag{2.8}$$

The solution of equation (2.8) is harmonic oscillation:

$$\alpha = \alpha_0\,cos(\omega_0 t + \varphi), \tag{2.9}$$

where α_0 is a maximal deviation angle of pendulum from position of equilibrium (amplitude of oscillations) ω_0 is angular frequency, φ is an initial phase (if in the initial moment of time a pendulum was maximally declined from position of equilibrium then $\varphi = 0$).

Period of oscillations is time needed to perform one full oscillation cycle. For the physical pendulum period T is

$$T = \frac{2\pi}{\omega_0} = 2\pi\sqrt{\frac{I}{mgL}}\,. \tag{2.10}$$

From the formula (2.10) it is possible to determine the free fall acceleration

$$g = \frac{4\pi}{T^2}\frac{I}{mL} \tag{2.11}$$

By formula (2.11), one has to determine the period of vibrations of rod and calculate its moment of inertia in order to calculate g.

3 DESCRIPTION OF EXPERIMENTAL APPARATUS

The pendulum used is a rod with mass m and length l. For a rod, the moment of inertia about an axis, that passes through the center of mass, is given by formula:

$$I_0 = \frac{1}{12}Ml^2, \tag{3.1}$$

and the moment of inertia about an axis, that passes through an upper end, may be found from parallel axis theorem :

$$I = I_0 + m\left(\frac{l}{2}\right)^2 = \frac{1}{3}Ml^2, \tag{3.2}$$

where we have used that the distance from the axis of rotation to the center of mass is

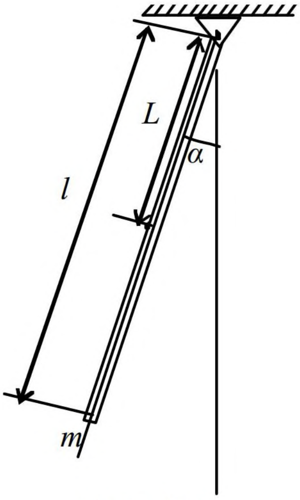


Figure 3.1

$$L = \frac{l}{2}. \qquad (3.3)$$

Taking into account expressions (3.1)-(3.3), it is possible to determine acceleration of the free falling from equation (2.11) to be

$$g = \frac{8\pi^2}{3} \cdot \frac{l}{T^2}. \qquad (3.4)$$

This there is a computation formula for determination of the free fall acceleration.

4 PROCEDURE AND ANALYSIS

4.1 Determine the length of rod l.

4.2 Determine the period T of oscillations of the physical pendulum. For that, use a stop-watch to measure time t of some number n (specified by teacher) of oscillations and calculate T from formula

$$T = \frac{t}{n}.$$

4.3 Repeat the experiment 3 times. Find the average value of T.

4.4 Calculate the value of the free fall acceleration from equation (3.4).

4.5 Estimate the errors of measurements of length and period and the error of mean value of period calculation.

4.6 Specify the value of relative error $\varepsilon = \left(\frac{\Delta l}{l} + 2\frac{\Delta T}{T} \right) \cdot 100\%$ and absolute error $\Delta g_m = \frac{g_m \cdot \varepsilon}{100}$.

4.7 Express results of the calculation in the form $g = g_m \pm \Delta g_m$.

4.8 Fill the table 4.1 with results of experiments and calculations.

Table 4.1

	***l*, m**	***Δl*, m**	***T*, s**	***ΔT*, s**	***g*, m/s^2**	***Δg*, m/s^2**	***ε*, %**
1	▨	▨			▨	▨	▨
2							
3							
Mean value							

5. CONTROL QUESTIONS

5.1 Formulate the law of universal gravitation.

5.2 What is the simple pendulum? What is the physical pendulum?

5.3 Write down an equation of harmonic oscillation.

5.4 Give definitions for amplitude, period, frequency, initial phase of oscillations?

5.5 What assumptions have been made in derivation of formula (2.8)?

Experiment M5

DETERMINATION OF LOGARITHMIC DECREMENT AND DAMPING COEFFICIENT OF OSCILLATIONS

Purpose of of the experiment: to master the basic concepts of theory of oscillations. To determine logarithmic decrement and damping coefficient.

1 EQUIPMENT

1. Pendulum with a scale.
2. Stop-watch.

2 THEORY

2.1 Harmonic oscillations are the variations of physical quantities in time, governed by low of sine or cosine:

$$\alpha = A\cos(\omega_0 t + \varphi_0), \qquad (2.1)$$

where α is a value of the varying quantity at the moment of time t, A is an amplitude of oscillations (the maximal value of physical quantity), $(\omega_0 t + \varphi_0)$ is a phase of oscillations (it determines deviation from equilibrium position), φ_0 is an initial phase (it determines deviation at the moment of time t=0), ω_0 is angular frequency.

Period of harmonic oscillations T is the time, required for completion of one full oscillation:

$$T = \frac{2\pi}{\omega_0} = \frac{1}{\nu}, \qquad [T]=1\ \text{s} \qquad (2.2)$$

ν is frequency of oscillations (number of oscillations per second). Unit of frequency is 1 Hz (cycle per second).

Harmonic oscillations can take place only under action of resilient forces (or other force which return the system to the equilibrium state and is proportional to the deviation from equilibrium $F = -k\alpha$, where α is deviation from equilibrium, k is coefficient of proportionality).

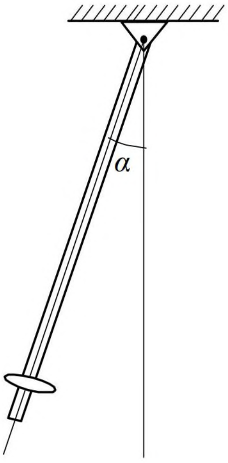


Figure 2.1

2.2 In real systems friction forces always impede motion. In this work the oscillations are studied on example of physical pendulum (Fig. 2.1). Physical pendulum is a body, that oscillates about a horizontal axis under action of force, that does not passes through the center of the masses of the body.

We may formulate the law of motion of physical pendulum on the basis energy conservation law taking into account that the pendulum rotates about fixed axis (see Fig. 2.1).

Moment of inertia I plays the same role in rotational motion as mass does in translational one. It means that is the moment of inertia is a measure of body’s inertia in rotational motion. One can see this from comparison of expression for kinetic energy in rotational motion of a body about a fixed axis ($I\omega^2/2$, where I denotes moment of inertia and ω stands for angular velocity) with expression for kinetic energy in translational motion of a body ($m\vartheta^2/2$).

The moment of inertia of a body of arbitrary geometrical form about some axis can be calculated using following equation

$$I = \sum_i \Delta m_i r_i^2 , \qquad (2.3)$$

stating that the moment of inertia of a rigid body about an axis equals to the sum of products of elementary masses (material points) and the square of their distances to the axis. If mass is distributed continuously the sum in previous equation evolves into the integral:

$$I = \int r^2 dm = \int r^2 \rho dV ,$$

where ρ stands for density, dV for elementary volume in the body, r is the distance from the elementary volume dV to the axis of rotation, and the integral is taken over all volume of the body. Unit of moment of inertia is 1 kg·m^2.

One can see that the value of moment of inertia depends on mass of the body, its size, form and the choice of rotation axis. Moment of inertia is additive quantity, which means that for the system consistsing of a few bodies a total moment of inertia equals to the sum of moments of inertia of individual bodies.

A body can rotate around a fixed axis on the condition that there is an external force $\vec{F}$ (or a component of a force), in plane perpendicular to the axis, acting on the body. The rotational effect of force $\vec{F}$ is characterized by a physical quantity named torque. A torque in rotational motion plays the same role as force does in translational motion. One may calculate torques about an axis or about a point, these differ in general case.

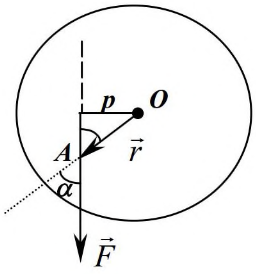


Figure 2.2

We choose the point O on the axis of rotation in the force $\vec{F}$ plane of action (see Fig. 2.2). The magnitude of the torque about fixed axis OZ is the projection of torque $\vec{\tau}$ about the point O onto an axis OZ:

$$\tau = Fr \sin\alpha . \qquad (2.4)$$

where α is angle between vectors $\vec{r}$ and $\vec{F}$, and $p = r\sin\alpha$ is the length of the perpendicular dropped from the axis of rotation on the line of action of the force, this perpendicular is called lever arm.

If there are several forces acting on a body, resulting (net) torque about a point O equals the sum of component torques.

Unit of torque is N·m.

In the arbitrary moment of time sum of kinetic and potential energies of pendulum equals

$$E = \frac{I\omega^2}{2} + \frac{k\alpha^2}{2} , \qquad (2.5)$$

where I is moment of inertia of pendulum about an axis, that passes through the point of suspension ω is angular velocity of pendulum at the given instant, m is mass of pendulum, g is acceleration of the free falling, d is distance from the axis of rotation of pendulum to the center of mass, α is an angle of deviation of pendulum from equilibrium position.

Reduction of the system energy dE during the displacement of pendulum by an angle $d\alpha$□ is caused by the loss of energy due to friction

$$dE = dA\,,$$

where elementary work of of friction forces torque τ_F is

$$dA = -\tau_F d\alpha\,, \tag{2.6}$$

the “minus” sign means that the force of friction leads to the decrease of the system energies ($dE<0$).

Suppose that torque of force of friction is proportional to angular speed:

$$\tau_F = r\omega\,, \tag{2.7}$$

where r is coefficient characterizing friction, ω is angular velocity ($\omega = \frac{d\alpha}{dt}$). Relation (2.7) comes from the analogy with forces of friction at the motion of material point (for example, simple pendulum).

As we have

$$dE = I\omega d\omega + k\alpha d\alpha\,,$$

then

$$I\omega d\omega + k\alpha d\alpha = -r\omega d\alpha\,.$$

Forasmuch

$$I\frac{d\omega}{dt} + k\alpha + r\frac{d\alpha}{dt} = 0\,,$$

or, taking into account, that

$$\frac{d\boldsymbol{\omega}}{dt} = \frac{d^2\boldsymbol{\alpha}}{dt^2}\,,\quad \frac{d\boldsymbol{\alpha}}{dt} = \boldsymbol{\omega}\,,$$

we have

$$\frac{d^2\alpha}{dt^2} + 2\beta\frac{d\alpha}{dt} + \omega_0^2\alpha = 0\,, \tag{2.8}$$

where notations $\beta = \frac{r}{2I}$ and $\omega_0^2 = \frac{k}{I}$ have been introduced. Quantity β is called the damping coefficient of oscillations, ω_0 is angular eigenfrequency of oscillations.

The equation (2.8) has solution in the form:

$$\alpha = A(t)\cos(\omega t + \varphi_0)\,, \tag{2.9}$$

which describes damped oscillations. Here $A(t)$ is amplitude of damped oscillations:

$$A(t) = A_0 \exp(-\beta t)\,, \tag{2.10}$$

A_0 is initial amplitude (at the moment $t=0$), ω is angular frequency of damped oscillations

$$\omega^2 = \omega_0^2 - \beta^2\,. \tag{2.11}$$

The period of damped oscillations is given by formula

$$\mathrm{T} = \frac{2\pi}{\omega} = \frac{2\pi}{\sqrt{\omega_0^2 - \beta^2}}\,. \tag{2.12}$$

Relations (2.9)-(2.12) take place only at condition $\omega_0^2 - \beta^2 > 0$, if $\beta^2 < \omega_0^2$ then oscillations do not appear because of significant resistance of environment.

3 DERIVATION OF COMPUTATION FORMULA

Let the amplitude of damped oscillations at the moment t_1 be

$$A_1 = A_0 e^{-\beta t_1}, \tag{3.1}$$

and corresponding amplitude at the moment t_2:

$$A_2 = A_0 e^{-\beta t_2}. \tag{3.2}$$

Divide (3.1) on (3.2) and get:

$$\frac{A_1}{A_2} = e^{-\beta(t_1 - t_2)} = e^{\beta(t_2 - t_1)} = e^{\beta \Delta t} = e^{\beta n \mathrm{T}}, \tag{3.3}$$

where n is number of complete oscillations made in time $\Delta t = t_2 - t_1$, $T = \dfrac{\Delta t}{n}$ is period of these oscillations. Taking logarithm of equation (3.3), we get

$$\ln \frac{A_1}{A_2} = \beta n T.$$

Where from

$$\beta = \frac{1}{nT} \ln \frac{A_1}{A_2} = \frac{1}{t} \ln \frac{A_1}{A_2}. \tag{3.4}$$

This equation means that damping coefficient is a quantity, reciprocal to the time, during which amplitude is reduced by factor *e* ($\ln(A_1/A_2)=\ln(e)=1$).

The logarithmic decrement of the oscillation damping is the quantity

$$\lambda = \beta T = \frac{1}{n} \ln \frac{A_1}{A_2}. \tag{3.5}$$

From a formula (3.5) it follows that logarithmic decrement is a quantity, reciprocal to the number of oscillations, during which amplitude is reduced by the factor *e*.

4 APPARATUS

The apparatus (Fig. 4.1) consists of physical pendulum, that can oscillate about the fixed axis and the electronic block for measuring the number of oscillations and their total time. The period of oscillation for the pendulum used can be changed by changing the position of the load on the bar. To start experiment one should to deviate the pendulum from position of equilibrium (to measure a deviation, angular degrees are marked on the scale), then clear the readings of the electronic block (pushing the button "CLEAR") and to release the pendulum. A photogate fixes the number of oscillations N and total time of oscillations t. Using these data it is possible to find the period of oscillations $T=t/N$. To stop counting oscillations at some moment (for example, at tenths oscillation), one should push the button of "STOP" during the last oscillation (in the above example, when reading of the electronic block is nine).

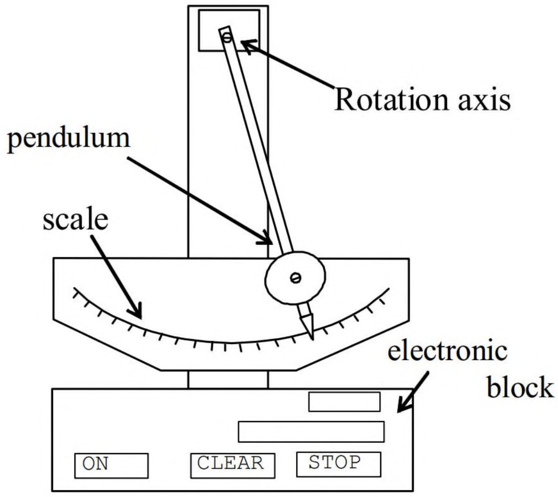


Figure 4.1

5 PROCEDURE AND ANALYSIS

5.1 Deviate the pendulum on angle A_1 (the value of A_1 is specified by lab assistant).
5.2 Set pendulum in motion. Determine the total time of N oscillations (N is specified by lab assistant) and final amplitude A_2.
5.3 Determine the damping coefficient and logarithmic decrement by formulas (3.4) and (3.5), respectively.
5.4 Carry out the experience three times.
5.5 Calculate the average values β_c and λ_c.
5.6 Estimate the errors of measurements and calculations.
5.13 Express results of the calculation in the forms $T = T_m \pm \Delta T_m$ and $\lambda = \lambda_c \pm \Delta\lambda_c$ and specify the value of relative error ε.
5.7 Fill the table 5.1 with results of experiments and calculations.

Table 5.1

	n	t, c	Δt, c	A_1, …°	ΔA_1, …°	A_2, …°	ΔA_2, …°	β, c^{-1}	$\Delta\beta$, c^{-1}	ε_β %	λ	$\Delta\lambda$	ε_λ %
1										▨			▨
2										▨			▨
3										▨			▨
Mean value													

4.3 Use formula (2.10) to find 5-6 additional values of amplitude in an interval [A_1, A_2] evenly placed in time. Plot graph of time dependence of amplitude.

6 CONTROL QUESTIONS

1. What is harmonic oscillation, and its basic characteristics?
2. What oscillations are called damped?
3. How does the amplitude of oscillations depends on time?
4. What is damping coefficient of oscillations?
5. Give definition of logarithmic decrement of damping.

Experiment M6

STUDY OF BASIC PRINCIPLES OF THERMODYNAMICS. DETERMINATION OF C_p/C_V FRACTION FOR AIR

Objective: to master the basic principles of molecular physics and thermodynamics. To determine C_p/C_V fraction for air experimentally.

1 EQUIPMENT

1. Hermetic container.
2. Manometer.
3. Pump.

2 THEORY

2.1 Ideal gas law.

The relation between gas parameters is known as ideal gas equation of state (ideal gas law). Only those gases we can treat as ideal in which, firstly, molecules are very small comparatively to volume of the container and, secondly, one can neglect interaction between molecules at distance. Equation of state for an ideal gas has the form:

$$pV = \frac{m}{\mu} RT, \tag{2.1}$$

where p stands for gas pressure on the walls of container (the unit of pressure is pascal, 1 Pa=1 N/m^2), V is volume of the container (in cubic meters), m is mass of the gas (in kilograms), μ is molar mass (the mass of one mole of gas, is measured in kilograms per mol), R=8,31 J/(mol·K) is the universal gas constant, T is absolute temperature (in kelvins, K).

If the gas pass from one state (p_1, V_1, T_1) to another (p_2, V_2, T_2) at constant temperature ($T_1=T_2$), the process is isothermal, and

$$p_1V_1 = p_2V_2 \quad (pV = const).$$

If the process take place at constant volume ($V_1=V_2$), then the process is isochoric (isovolumetric), and

$$\frac{p_1}{p_2} = \frac{T_1}{T_2}.$$

If $p_1=p_2$ (isobaric process), then

$$\frac{V_1}{V_2} = \frac{T_1}{T_2}.$$

2.2 Internal energy of an ideal gas

Internal energy is the total energy of all the thermal motions of molecules and their interactions. For one mole of ideal gas one can calculate the internal energy as a product of the mean kinetic energy of molecules $<\varepsilon_\kappa>$ and Avogadro's number N_A, and obtain

$$U = \langle \varepsilon_\kappa \rangle N_A;$$

$$\langle \varepsilon_{к} \rangle = \frac{i}{2} kT ,$$

where i is the number of degrees of freedom for a molecule (i=3 for one-atomic molecules, i=5 for two-atomic one and i=6 otherwise).

For arbitrary mass of a gas we have

$$U = \frac{i}{2} \cdot \frac{m}{\mu} RT . \tag{2.2}$$

2.3 The first law of thermodynamics is the law of energy conservation in application to thermal processes. It reads as

$$Q = \Delta U + A , \tag{2.3}$$

where Q is the heat, obtained by the system from outside, ΔU is the change of internal energy of system, A is the work, done by the gas.

In any process the total work done by external forces is

$$A = \int_{V_1}^{V_2} p dV . \tag{2.4}$$

2.4 The heat transferred to the gas in isochoric process can be expressed as

$$Q = \frac{m}{\mu} C_V \Delta T . \tag{2.5}$$

The quantity C_V is an important physical characteristic of a gas, namely a molar specific heat at constant volume

$$C_V = \frac{Q}{\frac{m}{\mu} \Delta T} ; \tag{2.6}$$

from the above equation one can see that C_V s determined by heat needed to warm up 1 mole of an ideal gas by 1 kelvin. Unit of molar specific heat is 1 J/(mol·K).

Analogously, in isobaric process, molar specific heat at constant pressure is

$$C_p = \frac{Q}{\frac{m}{\mu} \Delta T} ; \tag{2.7}$$

so, the molar specific heat at constant pressure is the heat needed to warm up 1 mole of an ideal gas by 1 kelvin.

For an ideal gas

$$U = \frac{i}{2} \cdot \frac{m}{\mu} RT ,$$

or

$$U = \frac{m}{\mu} C_V T ,$$

where

$$C_V = \frac{i}{2} R \tag{2.6}$$

is called the molar specific heat at constant volume

$$dU = \frac{m}{\mu} C_V dT .$$

In isobaric process we have

$$Q = \frac{m}{\mu}(C_V + R)\Delta T ,$$

where $\Delta T = T_2 - T_1$. And

$$C_p = C_V + R . \tag{2.9}$$

is the molar specific in isobaric process, so as

$$Q = \frac{m}{\mu} C_p \Delta T . \tag{2.10}$$

2.5 Adiabatic process

A thermodynamic process in which the system does not exchange the energy with its surroundings is known as adiabatic process. In adiabatic process heat transfer is absent

$$Q = 0. \tag{2.11}$$

The first law of thermodynamics for the adiabatic process reads as:

$$dU + pdV = 0 , \tag{2.12}$$

or

$$\frac{m}{\mu} C_V dT + pdV = 0 .$$

There is a relation between pressure and volume in adiabatic process called Poisson equation

$$pV^{\gamma} = const \text{ or } (p_1V_1^{\gamma} = p_2V_2^{\gamma}), \tag{2.13}$$

where

$$\gamma = \frac{C_p}{C_V} ,$$

is adiabatic index.

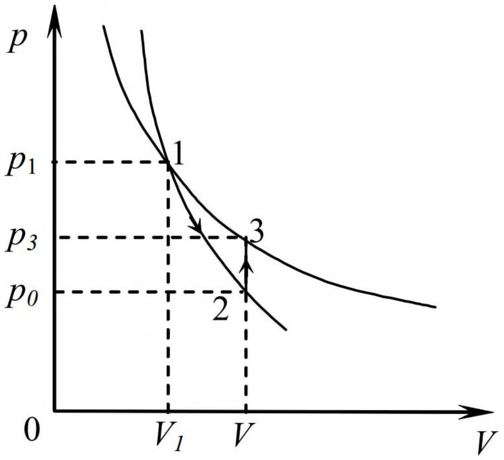


Figure 2.1

In figure 2.1 both adiabatic curve 1-2 and isotherm curve 1-3 are plotted, for comparison. One can see, that in adiabatic process the change in pressure is by much larger than in isothesmal process, at the same initial and final volumes. The reason of this is the following: in adiabatic expansion gas perform the work at expense of its internal energy only (no heat is supplied), so the gas temperature quickly decreases. Adiabatic exponent γ can be determined by method of Clemand and Desormes, in which isochoric and adiabatic processes are combined.

3 DESCRIPTION OF EXPERIMENTAL APPARATUS AND COMPUTATION FORMULA

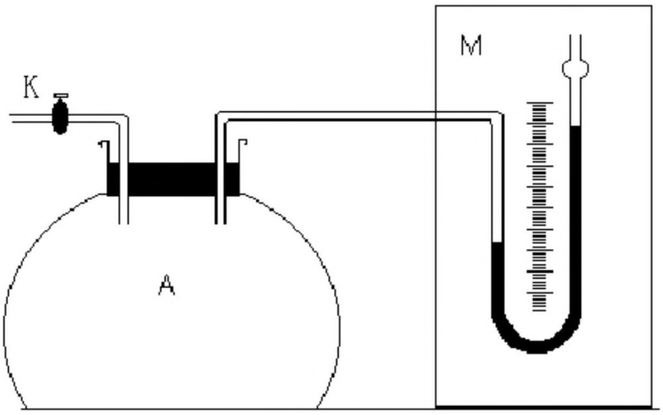


Figure 3.1

In this experiment we calculate the fraction C_P / C_V by method of Clemand and Desormes.

Container A is connected with manometer M and faucet K. The container can also be connected with the pump to fill it with air.

First, one has to even pressures within and outside the container A, by opening faucet K so that pressure within the container becomes equal to atmospheric pressure p_0 (water lewels in manometer M are equal). Then, by pumping air into the container the pressure is increased. At the same time, temperature increases, so one has to wait for a few minutes to obtain the thermal equilibrium of the air in container and surroundings (this is a isochoric process and the air volume does not change). After the thermal equilibrium is reached, the difference of levels h_1. in manometer is obtained. In this first state:

$$p_1 = p_0 + \rho g h_1. \tag{3.1}$$

(ρ is the density of liquid in manometer).

If the faucet K is opened and quickly closed again, the air expands adiabatically (segment 1-2 in fig. 2.1), as heat transfer is negligible for such a short process. After that, in the container pressure p_2 equals athmospheric pressure p_0 but temperature decreases $T_2 < T_1$. This is the second state. Transition from the first to the second state is described by Poisson equation:

$$p_1^{\gamma-1} / T_1^{\gamma} = p_0^{\gamma-1} / T_2^{\gamma}. \tag{3.2}$$

When equilibrium state is reached (pressure within the container is equal to athmospheric one) the faucet K is to be closed again. Gas in container is isochorically heated up (segment 2-3 in fig. 2.1) to temperature of the environment T_1, pressure within the container increases and a difference of liquid levels in manometer appear:

$$p_3 = p_0 + \rho g h_2, \tag{3.3}$$

where h_2 is the difference of levels in manometer. This is the third state of gas with parameters T_1 and p_3. Transition from the second to the third state is described by equation:

$$p_3 / p_0 = T_1 / T_3. \tag{3.4}$$

Which may be rewritten after taking into account equation (3.1) as:

$$[(p_o + \rho g h_1) / p_o]^{\gamma-1} = (T_1 / T_2)^{\gamma}, \tag{3.5}$$

or, equivalently

$$(1 + \rho g h_1 / p_o)^{\gamma-1} = [1 + (T_1 - T_2) / T_2]^{\gamma}. \tag{3.6}$$

Combining the former equation with equations (3.3) and (3.4) one onbtains

$$h_1 (\gamma - 1) / \gamma = h_2, \tag{3.7}$$

where from we obtain the calculation formula for C_P / C_V

$$\gamma = C_P / C_V = h_1 / (h_1 - h_2). \tag{3.8}$$

4 PROCEDURE AND ANALYSIS

4.1 Turn on a faucet K and let the levels of liquid in both legs of manometer M to equalize.
4.2 Join the container and the pump and fill the container with air until the difference of levels in manometer reaches 18-20 cm.
4.3 Turn off a faucet K and wait until the levels difference does not change (at these instance temperatures inside and outside the container are equal). Determine the difference of levels h_1 in manometer's legs.
4.4 For an instance, turn the faucet K to make levels in manometer equal and turn the faucet off quickly.
4.5 Wait 2-3 minutes until the air within the container is heated up to the room temperature (the levels in manometer stop changing). Determine the difference of levels h_2.
4.6 Repeat the experiment 4 times more.
4.7 Calculate the mean value $\gamma = C_p/C_V$ by formula (3.8).
4.8 Estimate the errors of measurements and calculations.
4.9 Express results of the calculation in the form $\gamma = \gamma_c \pm \Delta\gamma_c$ and specify the value of relative error ε.
4.10 Fill the table 4.1 with results of experiments and calculations .

Table 4.1

	h_1, 10^{-2} m	h_2, 10^{-2} m	γ	$\Delta\gamma$	ε, %
1					▨
2					
3					
4					
5					
Mean value	▨	▨			

5. CONTROL QUESTIONS

1. What is internal energy of an ideal gas?
2. What are quantity C_p, quantity C_V and their ratio?
3. Write and explain an equation of state for an ideal gas.
4. Give definition of isothermal, isovolumetric, isobaric and adiabatic processes.
5. What conclusions may be drawn from comparison of the experimentally obtained result and theoretical value γ for ideal gases?

Experiment M7

DETERMINATION OF SURFACE TENSION BY COMPARING LIQUID DROPS

Objective: to master conception of surface tension in liquid. To determine surface tension of the liquid under investigation by comparing liquid drops.

1 EQUIPMENT

1. Burette.
2. Studied liquid.
3. Distilled water.
4. Measuring glass.

2 THEORY

2.1 Molecules of water, as in any substance, are in constant motion. In distinction from gaseous media, strong interaction between molecules is inherent to liquid. Due to this interaction, molecules on the surface are in a different state from those being deep in volume (see fig. 2.1). Any molecule within the volume is surrounded by other molecules. The surrounding is symmetrical, the same molecules concentration and mean distances to them above, below, to the right, to the left for the given molecule. For this reason the averaged resultant force acting on the given molecule from side of the others is equal zero. In contrast to this, for a molecule on surface forces $\vec{F}_2$ from above vapor is much smaller than the forces $\vec{F}_1$ from below liquid, because the liquid is much more dense. The resultant of these forces is directed into the liquid, in consequence of it the surface layer presses onto below layers and creates an additional pressure in the liquid.

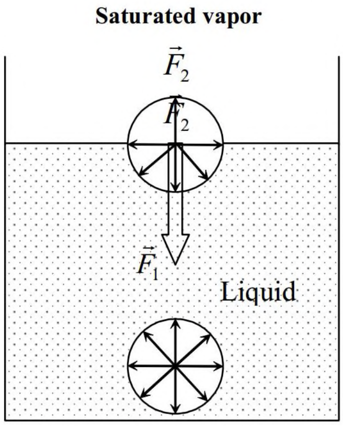


Figure 2.1

Total energy of molecules on surface differs from one for molecule deep inside the liquid. The energy difference of surface and in-volume molecules is known as the surface energy.

The number of surface molecules is proportional to the area of the surface, so any increase in the surface area *ΔS* result in the work *ΔA* done by the external forces to move molecules from inside the volume to the surface

$$\Delta A = \alpha \Delta S . \qquad (2.1)$$

Surface tension

$$\alpha = \frac{\Delta A}{\Delta S} . \qquad (2.2)$$

is defined as a work per area unit to increase surface by area unit. 1J/m^2 is a unit of surface tension.

As liquid has no rigid form, its surface in equilibrium state tends to have minimal energy. Due to the surface tension, in free state, liquid tends to take the form of the least volume, which is a sphere. In this way forces of surface tension appear, which cause the decrease of liquid's surface.

The force of surface tension on a segment of a surface layer is always normal to the contour and tangential to the surface. Magnitude of this force is proportional to the length of the contour

$$\Delta F = \alpha \Delta l . \tag{2.3}$$

From the above equation one can see that surface tension can also be defined as ratio of surface tension force ΔF, acting on the contour, to the length Δl of this contour

$$\alpha = \frac{\Delta F}{\Delta l} . \tag{2.4}$$

According to such definition, 1 N/m can also be taken as the unit of surface tension in SI system.

Every liquid is characterized by its own value of surface tension, dependent on a chemical composition of the liquid. Surface tension decreases with the increase of temperature and became zero at critical temperature.

3 DERIVATION OF COMPUTATION FORMULA

One can determine the surface tension for a liquid by comparing its drop's volume with other, standard one. If a liquid drips out of a burette B through faucet K (fig. 3.1). Surface tension does not allow the liquid to flow out of the burette freely and it drips out drop by drop. Every drop starts falling (see fig. 3.2) at the instance when weight of the drop exceeds the surface tension force

$$mg = F . \tag{3.1}$$

Taking into account, that tension force is $F = \alpha L$, where L is the circumference of the burette's end

$$L = 2\pi R , \tag{3.2}$$

here R is radius of the burette's end.

The tension force equals

$$F = 2\pi R \alpha . \tag{3.3}$$

Weight of the liquid drop is

$$mg = \rho V_x g , \tag{3.4}$$

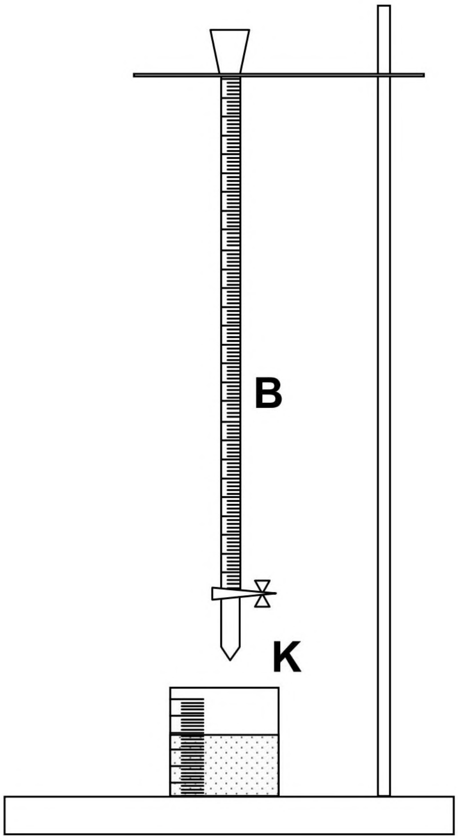


Figure 3.1

where V_x is volume of one drop, ρ is liquid's density. Equalizing right hand sides of equations (3.3) and (3.4), we obtain

$$2\pi R \alpha = \rho V_x g . \tag{3.5}$$

For distilled water one has

$$2\pi R_1 \alpha_1 = \rho_1 V_{x1} g . \tag{3.6}$$

For the studied liquid one has

$$2\pi R_2 \alpha_2 = \rho_2 V_{x2} g\,. \qquad (3.7)$$

Both liquids drips out of the same burette,so R_1=R_2. From system of equations (3.6) and (3.7) we find

$$\frac{\alpha_1}{\alpha_2} = \frac{V_{x1}\rho_1}{V_{x2}\rho_2} \qquad (3.8)$$

and, finally

$$\alpha_2 = \alpha_1 \frac{V_2 \rho_2}{V_1 \rho_1}\,. \qquad (3.9)$$

where V_1, and V_2 are volumes of water drop and studied liquid drop, respectively. This method allows to determine the surface tension for any liquid, comparing volumes of drops of two liquids.

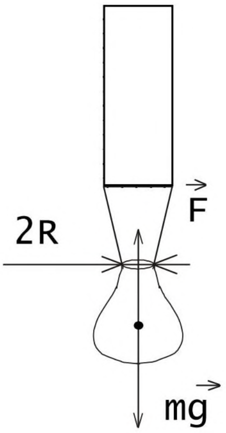


Figure 3.2

4 PROCEDURE AND ANALYSIS

4.1 Determine scale unit for the burette B in m^3.

4.2 Fill the burette B with distilled water, adjust faucet K until water drips out. Three times measure volume V_1 of a given number of drops n (to be specified by lab assistant).

4.3 Repeat the previous for the investigated liquid and determine volume V_2 for the same number of drops n.

4.4 Given the temperature in laboratory, find in tables the water density ρ_1, the density of investigated liquid ρ_2, the water surface tension α_1.

4.5 Calculate the value of surface tension for investigated liquid by formula (3.9).

4.6 Estimate the absolute and relative errors.

4.7 Represent the obtained results in the form $\alpha_2 = \alpha_{2c} \pm \Delta\alpha_{2c}$.

4.8 Fill the table 4.1 with results of measurements and calculations.

Table 4.1

	α_1, 10^{-3} N/m	$\Delta\alpha_1$, 10^{-3} N/m	V_1, 10^{-6} m^3	ΔV_1, 10^{-6} m^3	ρ_1, kg/ m^3	$\Delta\rho_1$, kg/ m^3	V, 10^{-6} m^3	ΔV_2, 10^{-6} м^3	ρ_2, kg/ m^3	$\Delta\rho_2$, kg/ m^3	α_2, 10^{-3} N/m	$\Delta\alpha_2$, 10^{-3} N/m	ε, %
1 **2** **3**	▨	▨			▨	▨			▨	▨	▨	▨	▨

5 CONTROL QUESTIONS

5.1 What is the origin of surface tension? What is surface energy?

5.2 Give the definitions to surface tension coefficient, specify its units of measurement.

5.3 What is surface tension force direction ?

5.4 In the absence of external forces a water drop is of spherical shape.Why is it so?

5.5 Use what you have learned from the kinetic molecular model to explain the reason of surface tension decrease with the increase of temperature.

Experiment M8

DETERMINATION OF THERMAL EXPANSION COEFFICIENT FOR A SOLID

Objective: to determine experimentally the thermal expansion coefficients for different metals

1 EQUIPMENT

1. Heater.
2. Test-tube.
3. Micrometer indicator of expansion.
4. Metal rods.
5. Vernier caliper.
6. Thermometer.

2 THEORY

2.1 At change of temperature of solids the dimensions of the bodies change (this phenomenon is explained by molecular theory). In broad temperature range the expansion is directly proportional to the temperature. Dependence of the body's length on temperature is determined by the formula

$$l = l_0(1+\alpha t), \qquad (2.1)$$

where l_0 is length of the body at 0°C, t is a temperature in Celsius, l is the length at the temperature t, α is called the linear coefficient of thermal expansion.

The linear coefficient of thermal expansion α may be defined as the relative change $\Delta l/l_1$ of the body's length at the 1 Kelvin change of temperature.

$$\alpha = \frac{\Delta l}{l_1 \Delta T} = \frac{\Delta l}{l_1 \Delta t}, \qquad (2.2)$$

here $\Delta l = l_2 - l_1$ is the absolute change of the length at temperature change from the value t_1 to t_2 (l_1 and l_2 are values of body's length at temperatures t_1 and t_2, respectively), $\Delta T = \Delta t = t_2 - t_1$ (note that 1˚C=1K). Actually, the temperature coefficient of thermal expansion also depends on temperature and, strictly speaking, the formula (2.2) is valid only for the mean value of the linear coefficient of thermal expansion in the temperature interval ΔT. 1 K^{-1} is the unit of coefficient of thermal expansion.

3 DESCRIPTION OF EXPERIMENTAL APPARATUS

The experimental apparatus for determination of the coefficient of thermal expansion includes the following parts (see fig. 3.1). The electric heater 1 is

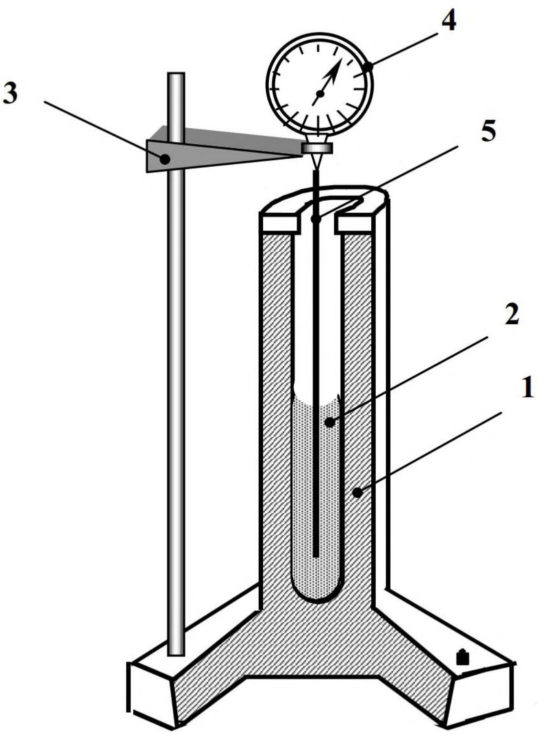


Figure 3.1

used to increase temperature of water in the test-tube 2. Metallic rod 5, which thermal expansion coefficient will be measured, is put in the water. In the holder 3 the micrometer indicator 4 is fixed. Using thermometer the initial temperature of water is measured. The initial length of the rod is measured with vernier caliper. After length of the rod is measured the rod is inserted into test-tube and indicator is put in contact with the upper end of the rod, the pointer is set to zero. The heater is on until the water start boiling. The absolute thermal expansion is read off the indicator. The final temperature is the boiling point (can be found from tables), corresponding to the value of air pressure in the laboratory.

4 PROCEDURE AND ANALYSIS

4.1 Measure the initial length l_1 of the first rod with vernier caliper.
4.2 Fill 2/3 of the test-tube with water and find its temperature t_1 by thermometer.
4.3 Put the rod under investigation into the test-tube (the rounded end down). Put the test-tube into the electric heater.
4.4 Insert the micrometer indicator into holder and put indicator’s spike in hollow on top of the rod. Fasten the indicator in the holder with screw.
4.5 Set the indicator pointer to zero point by turning a scale. Switch the heater on. Watch the motion of the pointer during the heating.
4.6 When the water in test-tube is boiling, the pointer stops. The final position of the pointer mark the total absolute expansion Δl of the rod. Turn the heater off.
4.7 Using table, determine the boiling point t_2 of water at the atmospheric pressure in the laboratory (determined from the laboratory barometer).
4.8 Calculate the value of linear coefficient of thermal expansion for material of the first rod using formula (2.4).
4.9 Repeat the experiment with other rods.
4.10 Estimate absolute and relative errors of the experiment.
4.11 Fill the table 4.1 with results of experiments and calculations.

Table 4.1

	l_2-l_1, 10^{-3} m	$\Delta(l_2$-$l_1)$, 10^{-3} m	l_1, 10^{-3} m	Δl_1, 10^{-3} m	t_1, °C	Δt_1, °C	t_2, °C	Δt_2, °C	α, 10^{-6} K^{-1}	$\Delta\alpha$, 10^{-6} K^{-1}	ε, %
1											
2											
3											

4.12 Express results of the calculation in a form $\alpha = \alpha_m \pm \Delta\alpha_m$ and specify the value of relative error ε.

5 CONTROL QUESTIONS

5.1. What is happened with solids at increase of temperature? Explain the reason of the expansion.

5.2. Write down the formula for dependence of the body’s length on temperature and explain it.
5.3. What is linear coefficient α of thermal expansion? What is unit of α in SI?
5.4. What substances have larger values of linear coefficient of thermal expansion?
5.5 Using the obtained value of linear coefficient α of thermal expansion, calculate the volume coefficient β of thermal expansion.

ELECTRICAL MEASUREMENTS

Electrical measurements include methods, devices and calculations aimed to measure electrical quantities (current, voltage, power, resistance, etc). There are different classifications of electro-measuring devices: by application, by accuracy, by principle of operation.

In the laboratory of electricity and magnetism voltmeters for voltage measurement, ammeters for electric current measurements, ohmmeters for electrical resistance measurements, wattmeters for electrical power measurements, oscilloscopes and multimeters are used. Beside the listed above direct measurement devices, different comparison schemes can be used, for example Wheatstone bridge and compensation method.

Quality of electro-measuring devices is determined by measurement limits, sensitivity, measurement errors, independence of external factors (electrical and magnetic fields, temperature changes, resistance to the overloads).

In order to apply an electro-measuring device, its scale factor and class of accuracy are to be found first.

Safety Measures

Electrical shock may cause serious injury or even death. Two types of electric current injuries are the most frequent. The first type happens if the current, flowing through the body, is comparable in magnitude with that of innervation impulses. If the current is flowing through arm or skin, it results in prickling, but if the heart muscle is involved, the consequences can be much more dangerous. In latter case the neuromuscular regulation is blocked and heart stops to pump blood to internal organs and to brain which results in necrosis. If the current is flowing through person's head, it can cause a cerebral affection.

One can distinguish between current intensity at which person feels action of current flowing in his tissues (threshold of sensation), intensity at which person can not take a hand off the source of voltage deliberately (not-let-go threshold) and intensity at which lethal outcome takes place. It is generally agreed, that threshold of sensation is about 0.001 A, not-let-go threshold is about 0.01 A and lethal threshold is 0.1 A though individual deviations can appear.

The total resistance of a human body is estimated to be 600 Ohms, so lethal voltage may be as low as 60 volts. To avoid electric shock, as primary practices in circuit assembling de-energize circuits, use protective gear and do not exceed instrument voltage and category ratings.

Measuring Device Sensitivity

Sensitivity $\boldsymbol{S}$ is determined by ratio of linear or angular deviation of the pointer $\Delta\alpha$ and measured quantity variation Δx

$$S = \frac{\Delta\alpha}{\Delta x}.$$

The greater sensitivity is, the greater is accuracy.

The quantity $C = \frac{1}{S}$ is called scale factor.

Accuracy Class of Device

For accuracy characterization reduced error

$$\varepsilon_r = \pm \frac{\Delta x}{x_{\max}} \cdot 100\%$$

is used, where Δx is absolute error of the measured quantity, $x_{\max}$ is the upper limit of the scale.

Class of accuracy equals the maximal reduced error. The upper limit of the absolute error (maximum error Δx_m) can be calculated as

$$\boxed{\Delta x_m = \frac{x_{\max} \cdot \varepsilon_{\max}}{100}}.$$

The existing accuracy classes for electric meters are 0.05; 0.1; 0.2; 0.5; 1.0; 1.5; 2.5; 4.0. For precise laboratory measurements devices with accuracy class from 0.05 to 0.5 are used. In technics, the devices with accuracy class from 1.0 to 4.0 are used.

If the accuracy class is not indicated, the absolute error is taken to be one half of the scale factor.

The Systems of Electro-measuring Devices

The principle of galvanometer's operation is based on the interaction of permanent magnet with the current-carrying coil (Fig. 5).

By principle of operation electro-measuring devices are classified as "moving-coil", "moving-iron", electrodynamic, electromechanical, induction, digital, etc.

A galvanometer of moving-coil system is a principal component of any DC ammeter or voltmeter.

Advantages of moving-coil system are high sensitivity, low energy consumption, equidistant scale.

Deficiencies are low breakdown voltage and current, ability to measure direct currents only.

If a moving coil galvanometer is combined with a rectifier, alternating currents can be measured with such combined device.

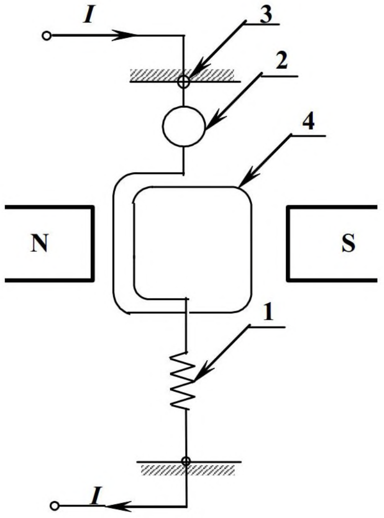


Fig. 5: 1 strip; 2 – mirror; 3 – suspender; 4 – moving loop

The principle of moving iron devices operation is based on the interaction of magnet field of the coil with moving ferromagnetic core (Fig. 6)

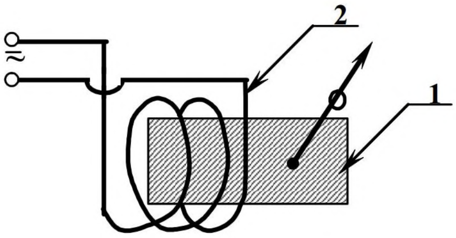


Fig. 6: 1 – moving iron bar, 2 – fixed coil

Advantages of moving ion devices are: resistance to the overloads, simplicity of construction, ability of DC and AC measuring.

Deficiencies are nonlinear scale, low sensitivity and accuracy, liability to influence of magnetic fields on the scale reading.

The principle of electrodynamic devices operation is based on the interaction of magnetic fields of a pair fixed coils, known as current coil, and a movable coil known as the potential coil (Fig.7).

In ammeters the coils are connected in parallel (the fixed coil is the shunt in this case). In voltmeter the coils are connected in series and in wattmeter fixed coil is connected in series and movable coil is connected in parallel to the consumer of energy.

Advantages of electrodynamic devices are: ability of DC and AC measuring, high accuracy.

Deficiencies are: low sensitivity and accuracy, nonlinear scale (except wattmeter), influence of magnetic fields on the scale reading

Other types of electro-measuring devices can use electromagnetic induction (induction system) or electric capacitance (electrostatic system) or other phenomena.

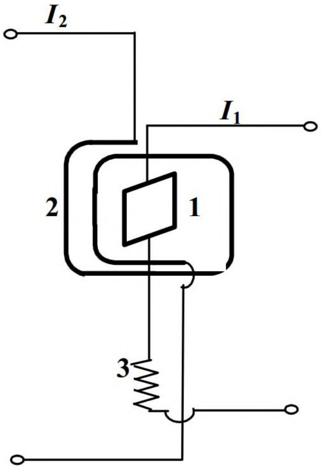


Fig. 7: 1 – moving loop; 2 – fixed coil; 3 – metallic strip (or isolated spiral)

Digital ammeter designs use an analog to digital converter (ADC) to measure the voltage across the shunt resistor; the digital display is calibrated to read the current through the shunt.

There is also a range of devices referred to as integrating ammeters. In these ammeters the amount of current is summed over time. As a result, the product of current and time is obtained, which is proportional to the energy transferred with that current. These devices can be used for energy meters (watt-hour meters).

For proper usage of electro-measuring device one must take into account the details of device’s construction and notations on the scale of the device. In Appendix A9 notation conventions for electro-measuring devices are given.

Experiment E1

STUDY OF ELECTRIC FIELD BY PROBE METHOD

Objective: to work out a theoretical model of electrostatic field using equipotential contours and electric field lines of electric dipole.

1 EQUIPMENT

1) Galvanometer;
2) metallic probes;
3) two electrodes;
4) bench insulator for electrodes and paper sheet;
5) emf source;
6) metallic leads;
7) ruler, pencil, paper, water.

2 THEORY

An electric charge creates an electric field in space surrounding it. If the charge is immobile, the field does not vary with time and is called electrostatic field. On any charge placed in the field, an electrical force is exerted. Such an action is a manifestation of the field and allows the estimation of its strength. The strength of the field in a point is characterized by a vector $\vec{E}$, which is called electric field. Numerically, magnitude of electric field E in some point is equal to the force acting on positive charge placed in this point divided by the charge magnitude:

$$\vec{E} = \frac{\vec{F}_\text{e}}{q_0}. \tag{2.1}$$

Direction of the vector $\vec{E}$ coincides with direction of the force acting on the charge. In practice, magnitude of the probing charge q_0 has to be small enough not to disturb the measured field.

If electric field in vacuum is created by point-like charge q, then the force, acting on the probing charge q_0 is determined by Coulomb's law:

$$F_\text{e} = \frac{q q_0}{4\pi\varepsilon_0 r^2}, \tag{2.2}$$

where r is the distance between centers of the charges; $\varepsilon_0 = 8{,}85 \cdot 10^{-12}$ F/m is the electric constant (also known as vacuum permittivity). Electric field, created by a point charge q on the distance r from the charge, is expressed by formula

$$E(r) = \frac{q}{4\pi\varepsilon_0 r^2}. \tag{2.3}$$

Within a dielectric medium the electric field is reduced:

$$E = \frac{E_0}{\varepsilon},$$

here E_0 is electric field in a vacuum; ε is known as dielectric permittivity of the medium ($\varepsilon \geq 1$).

A convenient way of visualizing electric field patterns is to draw lines that follow the same direction as the electric field vector at any point. These lines, called electric field lines, are related to the electric field in any region of space in the following manner. The electric field vector E is tangential to the electric field line at each point. The number of lines per unit area through a surface perpendicular to the lines is proportional to the magnitude of the electric field in that region. Thus, E is large when the field lines are spaced close together and small when they are far apart. If the lines at different locations point in different directions then the field is nonuniform.

The rules for drawing electric field lines are as follows. The lines must begin on a positive charge and terminate on a negative charge. The number of lines drawn leaving a positive charge or approaching a negative charge is proportional to the magnitude of the charge. No two field lines can cross.

Electric potential is an energy characteristic of electric field. Work done to move a charge q_0 between two points of the field, created by the point charge

$$A_{12} = \int_{r_1}^{r_2} \vec{F} d\vec{r} = \int_{r_1}^{r_2} \frac{q_0 q}{4\pi\varepsilon_0 r^2} dr = \frac{q_0 q}{4\pi\varepsilon_0}\left(\frac{1}{r_1} - \frac{1}{r_2}\right) = q_0(\varphi_1 - \varphi_2),$$

is dependent only on the magnitude of charge q_0 and electric potentials of initial point $\varphi_1 = \frac{q}{4\pi\varepsilon_0 r_1}$ and final point $\varphi_2 = \frac{q}{4\pi\varepsilon_0 r_2}$ but independent of the way along which the charge is moved.

For any electrostatic field, the difference of potentials $\varphi_1 - \varphi_2$ determines the change in energy, which is equal to the work done, so that

$$A_{12} = q_0(\varphi_1 - \varphi_2). \tag{2.4}$$

In a field one can find a surface all points of which have the same potential. This surface is known as **equipotential surface** (surface of constant potential).

Electric field lines are always perpendicular to equipotential surfaces. Electric force moving a unitary charge is equal in magnitude to $\boldsymbol{E}$ so the elementary work equals

$$\Delta A = E \Delta l \cos\alpha, \tag{2.5}$$

where Δl is a trajectory segment and α is angle between trajectory and force applied.

On the other hand, the work needed to move positive unitary charge from the point with potential φ to the point with $\varphi + \Delta\varphi$ equals to

$$\Delta A = \varphi - (\varphi + \Delta\varphi) = -\Delta\varphi, \tag{2.6}$$

where $\Delta\varphi$ is an increase of potential.

If the charge is moved along equipotential surface, the work done by electric field equals zero, because $\Delta\varphi = 0$. Comparing two above formulas for ΔA and taking into account that $\cos\alpha = 0$ for $\alpha = 90°$ we obtain that the electric field lines are perpendicular to equipotential surface.

One can express the value of electric field $\boldsymbol{E}$ through a gradient of potential $\frac{\Delta\varphi}{\Delta l}$ (change of potential $\boldsymbol{\Delta\varphi}$ corresponding to the unit of displacement in direction normal to equipotential surface):

$$E_l = -\frac{\Delta\varphi}{\Delta l}, \tag{2.7}$$

where $E_l = E \cdot cos\,\alpha$. One can see from formula (2.7) that electric field vector is directed towards lower potential: the condition $\Delta\varphi<0$ is to be fulfilled in order to get $E_l>0$.

Experimental setup for determination of electric lines and equipotential contours is shown in figure 2.1.

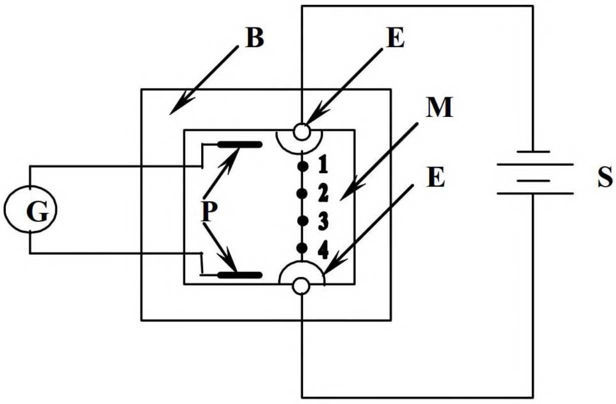


Figure 2.1

The insulating bench **B** is used to fasten a sheet of wet paper **M** (being a conducting medium) and electrodes **E** connected to source of direct current **S**. Prior to be fastened, the sheet of paper is to be moistened to make it conducting.

In this setup the electric field of a dipole is modeled by stationary electric field of direct current between electrodes in weakly conducting medium (wet paper). The source of emf maintains a constant voltage across electrodes and through the sheet of paper the constant current flows along the electric field lines. Measuring probes **P,** connected to galvanometer **G** allow one to determine voltage across chosen points and investigate the distribution of electrical potential.

3 PROCEDURE AND ANALYSIS

3.1 Draw an axis on a sheet of paper and divide the axis into segments each 3 cm long.

3.2 Moisturize the paper and fasten it with electrodes to the insulating bench.

3.3 Using galvanometer determine the distribution of potential along the axis. For this purpose press one of measuring probes to point 1 on axis and touch point 2 by the second probe. Read the voltage from galvanometer. Repeat the measurement with points 2 and 3 and so on.

Do not ever touch electrodes with measuring probes to avoid breakage of galvanometer.

3.4 Using formula (2.7) calculate the magnitude of electric field between points. Difference of potentials can be calculated by formula:

$$\Delta\varphi = n \cdot c \cdot R,$$

where *n* in deflection of galvanometer, *c* is graduation mark of the galvanometer, *R* is galvanometer’s resistance. Fill out table 3.1 with results of measurements and calculations:

Table 3.1

Distance between points, Δl	Galvanometer reading, n	Galvanometer's graduation mark, c	Resistance of the galvanometer, R	$\Delta\varphi$, V	E_l, V/m

3.5 To determine the form of equipotential contour, touch point 1 with one of the measuring probes and find 5-6 points aside the axis with the same value of potential (the galvanometer's pointer will point zero in this case). Connect all these points by a smooth line. This line represents an equipotential contour. Repeat this procedure for other points of the axis.

3.6 Having determined the form of equipotential contours, draw the electric field lines starting on the plus and ending on the minus (ground) electrode. Each of lines is to intersect the equipotential contours at right angles. Indicate voltage between the next nearest equipotential contours.

4. CONTROL QUESTIONS

1. What are characteristics of electric field in vacuum? Give definitions of E and φ and write formulas for these quantities. What are units of E and φ?
2. Formulate Coulomb's law.
3. Write formula for a work in electrostatic field and explain it.
4. What is the relation between the electric field vector and electric field potential?
5. What are electric field lines and equipotential surfaces? What are their properties?

Experiment E2

DETERMINATION OF SCALE GRADUATION MARK AND INTERNAL RESISTANCE OF GALVANOMETER

Objective: determination of scale graduation mark and internal resistance of galvanometer by shunt method.

1 EQUIPMENT

1) Galvanometer of magneto-electric system;
2) shunt (0-900 Ω);
3) resistor bank (0,01 Ω – 10000 Ω);
4) current source of known emf (accumulator or electrical element);
5) switches.

2 THEORY

A voltmeter is a device for measuring the voltage between two points in an electric circuit. Since one is interested in measuring the voltage between two points, a voltmeter must be connected in parallel with the part of the circuit on which the measurement is made. An ammeter is a device used to measure the flow of electric current in a circuit. Since one is interested in measuring the current flowing through a circuit component, the ammeter must be connected in series with the measured circuit component. Ideally, an ammeter should have zero resistance so that the current being measured is not altered. In real circuits the resistance of the ammeter should be much less than total resistance of the circuit. An ideal voltmeter has infinite resistance so that no current exists in it. In practice, this condition requires that the voltmeter have a resistance much greater than the resistance to which the voltmeter is connected in parallel. Note that a galvanometer can also be used as a voltmeter by adding an external resistor (shunt) in series with it. In this case, the external resistor must have a value much greater than the resistance of the galvanometer to ensure that the galvanometer does not significantly alter the voltage being measured.

Galvanometer is a sensitive measuring instrument without graduated scale. To measure current (or voltage) one has to know the graduation mark for the scale of the instrument. This value can be found either experimentally or from certificate of the instrument.

A graduation mark, denoted as C_a, is measured in Amperes per graduation mark and is used to calibrate ammeters. A graduation mark for voltmeter C_v is measured in volts per graduation mark. These coefficients are related by Ohm's law

$$C_v = C_a R_g , \qquad (2.1)$$

where R_g is an internal resistance of galvanometer.

A quantity inverse to coefficient $\boldsymbol{C}$ is known as sensitivity $\boldsymbol{S}$ of a galvanometer. The smaller the value of $\boldsymbol{C}$ is, the more sensitive the instrument is, and vice versa. Sensitivity of galvanometer can be changed by adding an external resistance (shunt). When a galvanometer is to be used as an ammeter, the shunt resistor R_s is connected in parallel to the galvanometer.

When one is going to measure voltage, the shunt is connected in series to the galvanometer. Shunting makes it possible to broaden the limits of a measurement for a given galvanometer.

The goal of this experiment is to determine the internal resistance and conversion coefficients for galvanometer by shunt method.

Since in measuring devices of magneto-electric system the pointer deviation is directly proportional to current passing through galvanometer, the graduation mark C_a has constant value as well, so the current intensity I at deviation to n'th scale mark is

$$I = C_a \cdot n. \tag{2.2}$$

A diagram of the circuit designed for determination of graduation mark C_a and galvanometer's internal resistance R_g is given in Fig. 2.1. Here **G** denotes a galvanometer, E is emf source, R_s is shunt resistance, R is a set of resistors. Let us use the following notations: at the value of load resistance R=R_1 and shunt disconnected the value of current is I_1, at R=R_2 and shunt connected the value of current is I_2. By using Kirchhoff's first rule (or Ohm's law for a closed circuit) in both mentioned cases one obtains:

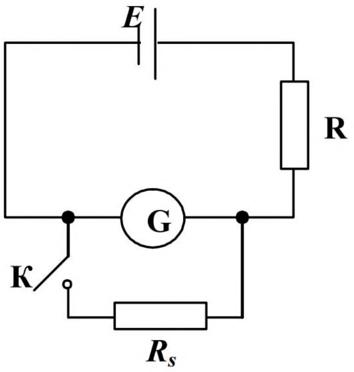


Figure 2.1

$$E = I_1\left(R_g + R_1\right) = C_a n_1\left(R_g + R_1\right), \tag{2.3}$$

$$E = I_2\left(R' + R_2\right). \tag{2.4}$$

Here resistance of connecting wires and internal resistance of emf source are neglected. Equivalent resistance R' of galvanometer-shunt parallel connection equals

$$R' = \frac{R_s R_g}{R_s + R_g}.$$

By Kirchhoff's first rule $I_2 = I_g + I_s$, where I_g is the current flowing through galvanometer, and I_s is that for shunt. The ration of current values in each branch is inversely proportional to the branch's resistances, thus

$$\frac{I_g}{I_s} = \frac{R_s}{R_g},$$

hence

$$I_s = I_g \frac{R_g}{R_s};$$

$$I_2 = I_g + I_s = I_g\left(1 + \frac{R_g}{R_s}\right).$$

Substituting I_2 and R' in formula (2.4), one has (I_2=$C_a \cdot n_2$)

$$E = C_a n_2 \left(1 + \frac{R_g}{R_s}\right)\left(R_2 + \frac{R_s R_g}{R_s + R_g}\right). \tag{2.5}$$

Solving the system of equations (2.3) and (2.5) with respect to R_g and C_a, one obtains

$$R_g = \frac{R_s(n_1 R_1 - n_2 R_2)}{n_2(R_2 + R_s) - n_1 R_s}, \tag{2.6}$$

$$C_a = \frac{E}{n_1(R_g + R_1)}. \tag{2.7}$$

4 PROCEDURE AND ANALYSIS

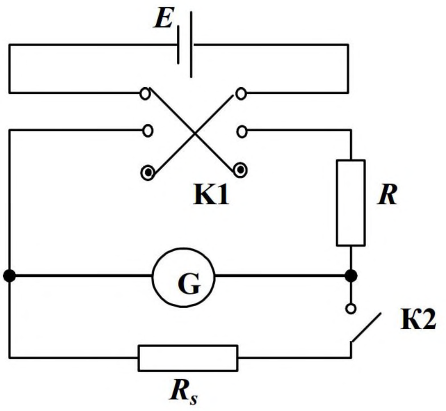


Figure 3.1 Electric diagram for galvanometer characterization

3.1 Assemble electric circuit according to diagram shown in Fig. 3.1 without connecting emf source. All switches must be off.

3.2 Set resistance R to have maximum value. Check the pointer of galvanometer matching zero of scale and tune it, if necessary.

3.3 After verification of circuit by lab assistant, connect emf source and start measurements.

3.4 Set switch K1 on, then find a value R_1 of load resistance, at which galvanometer pointer will be at 2/3-scale deflection. Note number n_1 of scale marks and value R_1 of resistance.

3.5 Using the switch K1 change direction of current and note scale mark n'_1 for deflection in opposite side. Set switch K1 off and maximum resistance R.

3.6 Connect shunt R_s by setting switch K2 on and find a value R_2 of the load resistor at which full-scale deflection is observed on galvanometer. Note the number n_2 of scale marks in this case.

3.7 Change the current direction for the opposite by switch K1 and note the deflection n'_2. Determine the value of shunt resistance R_s used.

3.8 Repeat the experiment two more times for any other values of shunt resistance. Fill out table 3.1 with results of measurements and calculations:

Table 3.1

	Galvanometer scale deflection at shunt disconnected			Resistances			Galvanometer scale deflection at shunt connected		
	n_1	n'_1	$n_0 = \frac{n_1 + n'_1}{2}$	R_1	R_2	R_s	n_2	n'_2	$n = \frac{n_2 + n'_2}{2}$
1.									
2.									
3.									
Mean value									

3.9 Calculate the internal resistance and graduation marks by formulae (2.6), (2.7), (2.1).

3.10 Calculate absolute and relative errors and mean values of R_g, C_a and C_v.

5. CONTROL QUESTIONS

1. What is the function of ammeter? How is it connected in circuit?
2. What is the function of voltmeter? How is it connected in circuit?
3. What is graduation mark?
4. How can one change the graduation mark of measuring devices?
5. What is shunt and how must it be connected to galvanometer for measurements of current or voltage?

Experiment E3

DETERMINATION OF RESISTANCE WITH WHEATSTONE BRIDGE

Objective: to study direct current laws and master Wheatstone method of resistance determination.

1 EQUIPMENT

1) Current source of known emf;
2) galvanometer of magneto-electric system;
3) variable resistor;
4) studied resistors;
5) rheochord, rheostat;
6) switch and connecting wires.

2 THEORY

Electric current is the flow of electric charges through a conductor. The current depends on the material through which the charges are passing and the potential difference across the material. The current value is the rate at which charge flows through this surface. If *dq* is the amount of charge that passes through this area in a time interval *dt*, the current *I* is equal to the charge that passes through cross section per unit time:

$$I = \frac{dq}{dt}. \qquad (2.1)$$

The SI unit of current is Ampere (1A= 1 C/ 1 s).

It is conventional to assign to the current the same direction as the flow of positive charge. In metallic conductors, such as copper or aluminium, the current is due to the motion of negatively charged electrons. In metals the number of free electrons able to conduct current is of order of 10^{28} per 1 m^3. In some cases, such as those involving gases and electrolytes, for instance, the current is the result of the flow of both positive and negative charges.

If the ends of the conducting wire are connected to a battery, the battery sets up a potential difference between the ends of the loop, creating an electric field within the wire. The electric field exerts forces on the conduction electrons in the wire, causing them to move, thus creating a current. A current that is constant in direction is called a direct current (DC). It is common to refer to a moving charge (positive or negative) as a mobile charge carrier. Electric resistance is due to scattering of charge carriers by vibrations of positively charged ions, which are by far heavier than electrons. For this reason electric resistance is temperature-dependent: the higher the temperature, the more intensive are ion vibrations and, as a consequence, the higher is the electrical resistance of conductor.

There are several experimental methods for measuring a resistance. Conventional methods utilize ohmmeter, ammeter and voltmeter or Wheatstone bridge.

Ohmmeter is a galvanometer with scale graduated in resistance units. The higher the resistance of circuit is, the smaller is the deflection of the scale. This allows to measure resistance directly, but the method has low accuracy. One may use combined **ammeter**

and voltmeter to measure both current and voltage and then calculate the value of resistance by Ohm's law.

The method of **Wheatstone bridge**, shown in figure 2.1 is more accurate than the methods described above. The circuit is composed of rheochord **AC**, sensitive galvanometer **G** and two resistors. Value of one of the resistors is known and is equal to R_0 and the other resistor is of unknown value R_x. A reochord (also known as a slide-wire) is a homogeneous wire of constant cross-section, along which a slide-bar **D** can slide.

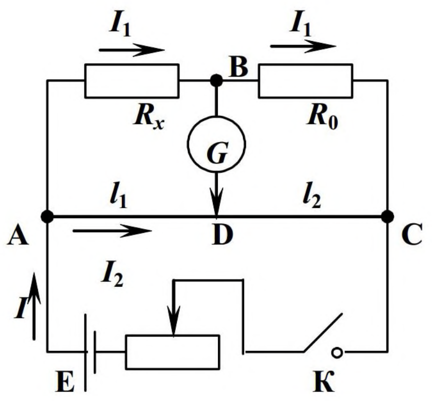


Figure 2.1

Consider the circuit shown in Figure 2.1 without the segment **BD**. If the switch **K** is on, current I_2 starts flowing through wire **AC**, along the wire some distribution of potential is set. The highest potential φ_A is set at point **A** and the lowest value φ_C is in point **C**. In segment **ABC,** there will be current I_1 flowing at these conditions and electric potential will be changing from φ_A to φ_B on the resistor R_x and from value φ_B to φ_C on the resistor R_0. Obviously, at point B the potential has an intermediate value φ_B ($\varphi_A>\varphi_B>\varphi_C$). In consequence of this, there is a point **D** on the segment **AC** the potential φ_D of which has the same value, as the potential φ_B of point **B.** If a galvanometer is connected across points **B** and **D,** no current flows through it because electric potentials of these points have the same value, $\varphi_D=\varphi_B$. Under this condition the bridge is said to be balanced. The balance condition can be derived using two principles called Kirchhoff's rules. The first of these states that the algebraic sum of the currents entering and leaving any junction in a circuit must equal zero:

$$\sum_{i=1}^{n} I_i = 0, \tag{2.2}$$

where n is number of currents entering and leaving the junction. This equation is also called the Kirchhoff's junction rule. A junction is any point in a circuit where a current can split. This split results in a smaller current flowing in each individual resistor than the value of the current from the battery. Because electric charge is conserved, the current that enters junction must be equal to the total current leaving that junction.

The second rule (Kirchhoff's loop rule) states the following. The sum of the voltages across all elements around any closed circuit loop must be equal to the sum of emf's around the circuit:

$$\sum_{i=1}^{n} I_i R_i = \sum_{i=1}^{k} \varepsilon_i, \tag{2.3}$$

where I_i is current in ith element of the circuit; R_i is ith element's resistance; ε_i is emf of ith source; n is number of elements with resistance; k is number of elements with emf.

Using the loop rule for subcircuits **ABD** and **BCD** we obtain:

$$\begin{aligned} I_1 R_x - I_2 r_{AD} &= 0; \\ I_1 R_0 - I_2 r_{DC} &= 0. \end{aligned} \tag{2.4}$$

Solution of system (2.2)-(2.3) expresses the balance condition for Wheatstone bridge as:

$$\frac{R_x}{R_0} = \frac{r_{AD}}{r_{DC}}. \tag{2.5}$$

Since resistances of segments **AD** and **DC** of rheochord are proportional to their lengths $\boldsymbol{l_1}$ and $\boldsymbol{l_2}$, we have

$$R_x = R_0 \frac{l_1}{l_2}. \tag{2.6}$$

If total length of the rheochord is $\boldsymbol{l}$, then $\boldsymbol{l_2 = l - l_1}$, and

$$R_x = R_0 \frac{l_1}{l - l_1}. \tag{2.7}$$

The above equation is used as a computation formula in present experiment.

By Wheatstone method one can also determine equivalent resistance of resistors connected in parallel or in series. These experimental results are to be compared with ones calculated theoretically. For resistors, connected in series (as links in chain), the same current passes through all of the resistors in a given time interval. The voltage across the whole series is calculated as a sum of voltage across the first resistor plus the voltage across the second and so one. As a consequence, the equivalent resistance equals the sum of all individual resistances connected:

$$R = \sum_{i=1}^{n} R_i. \tag{2.8}$$

The resistance R is equivalent to the series combination of all R_i in the sense that the circuit current is unchanged when R replaces the combination of R_i.

For resistors connected in parallel, the potential difference across terminal junctions has the same value for all of the resistors. Since voltages are equal and, by Kirchhoff's junction rule, a current splits up in parts, inversely proportional to resistances of particular conductors, we obtain inverse of equivalent resistance for the parallel connection as

$$\frac{1}{R} = \sum_{i=1}^{n} \frac{1}{R_i}. \tag{2.9}$$

These relationships indicate that the equivalent resistance of a series connection of resistors is always greater than any individual resistance, and resistance of a parallel connection is less than any of individual resistances.

3 PROCEDURE AND ANALYSIS

3.1 Assemble electric circuit according to diagram shown in Fig. 3.1.

3.2 Set resistance $\boldsymbol{R}$ to a maximum value.

3.3 Set slide-bar **D** in center of reochord **AC** and vary the resistance $\boldsymbol{R_0}$ until galvanometer **G** reading becomes zero at making the switch **K** on.

3.4 Set resistance of rheostat to minimum value and vary the resistance $\boldsymbol{R_0}$, then move slide-bar **D** until the galvanometer's reading is zero again.

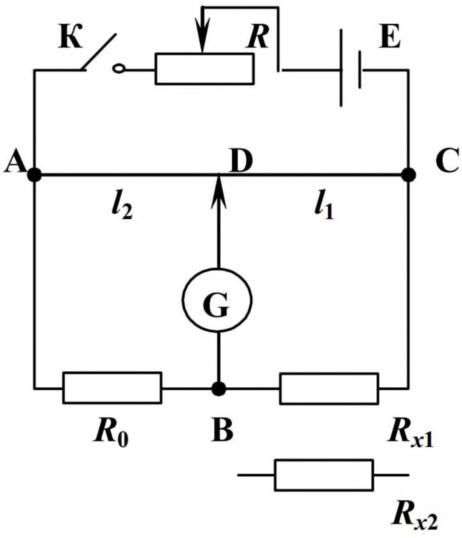


Figure 3.1

3.5 Fill the table 3.1 with obtained results for R_0, l_1 and l_2.

3.6 Repeat the measurements for two more values of resistance R_0, one 10% higher, the other 10% lower than the initial value. The galvanometer reading is set to zero by moving slide-bar **D.**

3.7 Analogously, R_{x2}, as well as parallel and series configurations of R_{x1} i R_{x2} are investigated.

Note that the circuit is to be completed only for a very short time (just to take galvanometer's reading) because the passing current will heat up the conductors and consequently change the values of resistances.

3.8 Values of unknown resistances are calculated by formula (2.7). Absolute and relative errors are calculated for series of measurements. Fill out table 3.1 with results of experiments.

3.9 Calculate the equivalent resistances for in series and in parallel connections by formulae $R_{ser} = R_{x1} + R_{x2}$ and $\frac{1}{R_{par}} = \frac{1}{R_{x1}} + \frac{1}{R_{x2}}$, respectively, and compare theoretical and experimental results.

Table 3.1

Resistance		**R_0, Ω**	**l_1, mm**	**l_2, mm**	**R_x, Ω**	**ΔR_x, Ω**	**$R_{mean.}$, Ω**	**$\Delta R_{mean.}$, Ω**	**ε_x, %**
R_{x1}	**1**								
	2								
	3								
R_{x2}	**1**								
	2								
	3								
In series R_{x1} and R_{x2}	**1**								
	2								
	3								
In parallel R_{x1} and R_{x2}	**1**								
	2								
	3								

4 CONTROL QUESTIONS

1.What is electric current? What are units of current?
2. List and characterize the methods of resistance measurement.
3. Formulate the Kirchhoof's rules.
4. Write the formula for equivalent resistance of series connection and explain it.
5. Write the formula for equivalent resistance of parallel connection and explain it.

Experiment E4

DETERMINATION OF HORIZONTAL COMPONENT OF THE EARTH'S MAGNETIC FIELD USING HELMHOLTZ COIL

Objective: To determine the horizontal component of the Earth's magnetic field using Helmholtz coil.

1 EQUIPMENT

1) Power source;
2) Helmholtz's coil;
3) compass;
4) milliammeter;
5) rheostat.

2 THEORY

The planet Earth has its own magnetic field. Though relatively weak, this field is able to rotate magnetic needle of a compass and is widely used in navigation. Other important effect of the Earth's magnetic field is its action on the charged space particles. These particles are declined by magnetic field and hit in atmosphere mostly in polar regions. This causes a well known atmospheric phenomenon called northern lights (aurora borealis). Magnetic needle is ordered in parallel with the magnetic field $\vec{B}$ at a given point. This direction is tangential to magnetic field line which passes through this point (see fig. 2.1). The magnitude of $\vec{B}$ for the Earth are in range from $0.42\cdot10^{-4}$ T on equator to $0.70\cdot10^{-4}$ T at poles. The most probably, liquid iron core of our planet is the source of the Earth's magnetic field.

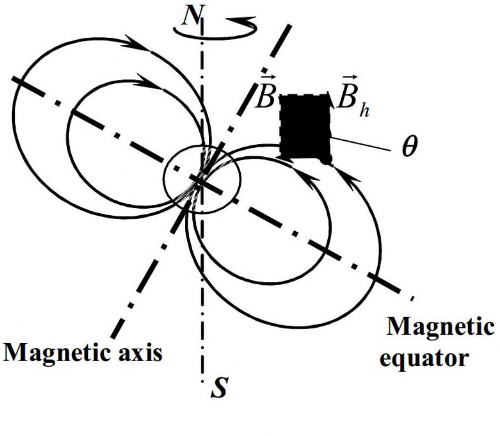


Figure 2.1

One can measure the horizontal component $\vec{B}_h$ of the Earth's magnetic field by Helmholtz coil, composed by two planar coils (or two loops), arranged in parallel at a distance equal to the radius of the coil.

If the symmetry axis **OO₁** of Helmholtz coil is perpendicular to the magnetic meridian plane then the magnetic field $\vec{B}_0$ of a current in this coil tends to decline a magnetic needle in a compass from its direction along the magnetic meridian of the Earth. Taking into account that direction the magnetic needle is determined by the resultant magnetic field (see Figure 2.2) one can express the magnetic field of the Earth through the magnetic field of the coil and the angle α of declination as

$$tg\alpha = \frac{B_0}{B_h}. \qquad (2.1)$$

Magnetic field $\vec{B}_0$ of a current loop on its axis **OO₁** is directed along the noted axis, as a result of superposition of elementary magnetic fields $d\vec{B}$ created by every segment *dl* of the loop. The direction of the resulting magnetic field vector can be determined by the **right-hand-rule**: if one wraps the right hand around the loop with fingers in the direction of the current, the thumb points in the direction of the magnetic field vector (see fig. 2.3).

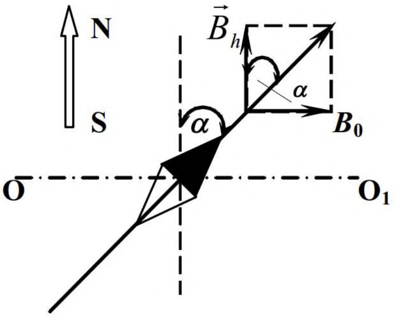


Figure 2.2

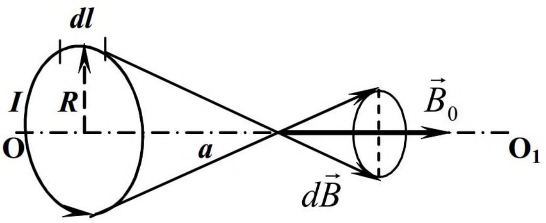


Figure 2.3

Besides the magnetic field vector $\vec{B}$, magnetic field strength $\vec{H}$ is widely used for the field description (especially useful for the field inside magnets).

The magnitude of magnetic field strength on coil's axis is given by formula

$$H = \frac{I \cdot n \cdot R^2}{2\left(R^2 + a^2\right)^{3/2}}, \tag{2.2}$$

where ***R*** stands for the radius of the coil, ***a*** is the distance from the coil's center to the point of measurement, ***n*** is number of turns in the coil. This formula may be obtained using Bio-Savart law and superposition principle. Magnetic field $\vec{B}_0$ itself is connected with magnetic field strength $\vec{H}_0$ by relation

$$\vec{B}_0 = \mu\mu_0\vec{H}_0, \tag{2.3}$$

where μ_0 is magnetic constant (μ_0=4π·10^{-7} H/m), μ is magnetic permeability of the medium ($\mu \approx 1$ for an air). Magnetic field lines which are used to describe a magnetic field are always closed and in every point the magnetic field $\vec{B}$ is tangential to the magnetic lines (see fig. 2.1).

Since the Helmholtz coil is constructed of two planar coils, placed at a distance ***R*** apart, their fields are superposed. The total field in a center is given by

$$H_0 = \frac{I \cdot n \cdot R^2}{\left(R^2 + R^2/4\right)^{3/2}} = \frac{8}{5\sqrt{5}} \cdot \frac{I \cdot n}{R} = 0{,}7156 \cdot \frac{I \cdot n}{R}, \tag{2.4}$$

$$B_0 = 8{,}988 \cdot 10^{-7} \cdot \frac{I \cdot n}{R}. \tag{2.5}$$

From these considerations we obtain the following expressions for the horizontal component of the Earth's magnetic field

$$H_h = \frac{0.7156}{tg\alpha} \cdot \frac{I \cdot n}{R}, \text{ (A/m)} \tag{2.6}$$

$$B_h = \frac{8.988 \cdot 10^{-7}}{tg\alpha} \cdot \frac{I \cdot n}{R}. \text{ (T)} \tag{2.7}$$

4 PROCEDURE AND ANALYSIS

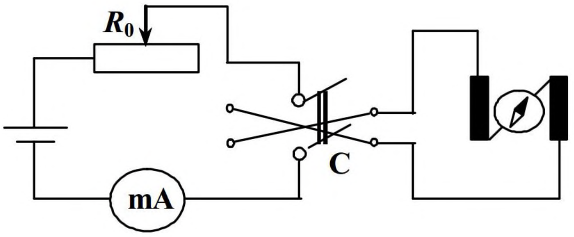


Figure 3.1

3.1 Assemble circuit as shown in fig. 3.1.

3.2 Arrange the Helmholtz coil along magnetic meridian using compass. On a compass scale the magnetic needle should point towards zero.

3.3 Switch on current and using rheostat change its magnitude. In this way point the magnetic needle to 30° on the scale of compass. By ammeter, determine the current magnitude which corresponds to this angle.

3.4 Repeat the measurement for 45° i 60°.

3.5 Determine radius ***R*** of the coil and number ***n*** of turns in it.

3.6 Calculate the values of ***H*** and ***B*** from formulae (2.6) and (2.7).

3.7 Fill out table 4.1 with results of experiments and calculations.

Table 4.1

	α	***I*, A**	***n***	***R*, m**	***B* T,**	***H*, A/m**
1						
2						
3						
Mean value						

5 CONTROL QUESTIONS

1. What is the probable reason of the Earth's magnetic field existence?
2. What are components of Helmholtz coil? Explain reasons of the magnetic needle declination.
3. Explain the formula (2.2) for magnetic field strength on axis of the coil.
4. Formulate the right-hand-rule for the direction of magnetic field on the coil axis.
5. Explain the relation between magnetic field strength and magnetic field vector. Specify their units.

Experiment E5

THERMOCOUPLE CALIBRATION

Objective: to learn elementary theory of Seebeck effect and to calibrate a thermocouple.

1 EQUIPMENT

1) Thermocouple;
2) Galvanometer;
3) Thermometer;
4) Thermostat;
5) Voltmeter;
6) Resistors, connecting wires and switch;
7) Battery of known emf;
8) Electric heater.

2 THEORY

Back in the 18th century, Alessandro Volta found that two chemically different metals produce the contact potential, which is dependent only on their chemistry and temperature (Volta's first law). If a few conductors made of different metals are connected in series, there occurs a potential difference between outermost conductors. This potential difference is not dependent on materials placed between the outermost conductors and is determined only by the properties of the outermost conductors (Volta's second law).

Occurrence of the contact potential difference can be a manifestation of thermoelectric emission and its different character for different contacting materials. Electrons of metal can leave their host metal if their kinetic energy is higher than workfunction ϕ (this work is needed to overcome attraction of negative electrons and positive ions). At some temperature there is always some number of electrons able to temporarily leave the metal and then come back due to attraction of ions. Thus, over the surface of metals a negatively charged "electronic cloud" is formed and the surface itself has the net positive charge. These charges create potential difference known as contact potential. Every metal has some characteristic value workfunction and contact potential. The value of contact potential depends on temperature and surface purity of materials in contact. The other possible cause of contact potential difference is the electron concentration difference of different metals. Electrons are redistributed through the junction to equalize concentrations across the junction, until the produced electric field prevents the further redistribution.

If two heterogeneous metals **A** and **B** are joined together as shown in fig. 2.1, in equilibrium state there occur charged bilayers in junctions 1 and 2. If temperatures of both junctions are the same, sum of contact potentials along the **A-B** circuit equals zero. If temperatures of junctions are maintained at different temperatures t_1^o i t_2^o, contact potential differences becomes different due to their temperature dependence and there a thermo-emf occurs

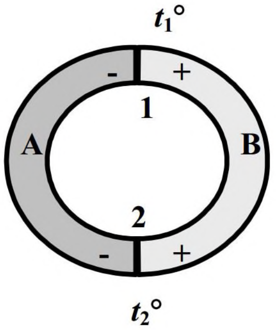


Figure 2.1

$$\varepsilon = \alpha \cdot \left(t_1^\text{o} - t_2^\text{o}\right), \qquad (2.2)$$

where α is Seebeck (or thermo-emf) coefficient for a given pair of metals (this effect is also known as Seebeck effect). The magnitude of α is of order of ~10^{-5} V/°C for metals and ~10^{-3} V/°C for semiconductors. Thermo-electric thermometers use Seebeck effect and serve for measuring of temperatures, for which usual thermometers are inapplicable.

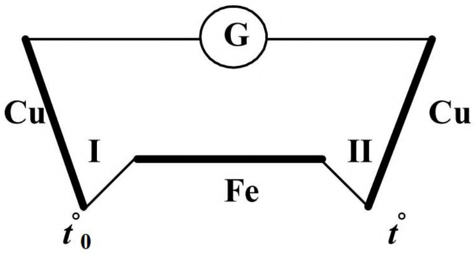


Figure 2.2

Consider a circuit, in which thermo-couple is connected to a sensitive galvanometer and one of soldered junctions is maintained at constant temperature t_0^o (see fig. 2.2). If the metals of thermocouple are properly chosen, the magnitude of α is constant in a wide temperature range. Then the current flowing through the galvanometer is directly proportional to the temperature difference between the junctions. If a scale deflection of the galvanometer is ***N*** points for thermo-emf ε, then

$$\varepsilon = C \cdot N, \qquad (2.3)$$

where ***C*** is galvanometer's graduation mark. By substitution of **ε** in formula (2.3) with $\alpha\left(t^\text{o} - t_0^\text{o}\right)$, one obtains

$$\alpha\left(t^\text{o} - t_0^\text{o}\right) = C \cdot N,$$

and, finally, Seebeck coefficient for the used thermo-couple is

$$\alpha = \frac{C \cdot N}{t^\text{o} - t_0^\text{o}}. \qquad (2.4)$$

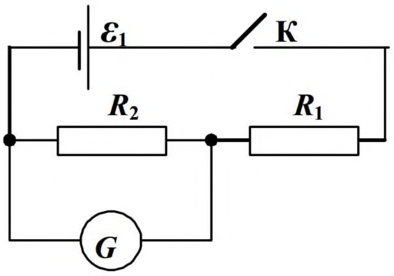


Figure 2.3

If the value of ***C*** is not given, it can be found with use of the circuit shown in fig. 2.3.

If a scale deflection is ***N*** points after switch **K** is closed, the galvanometer's graduation constant is

$$C = \frac{V}{N},$$

here V is the voltage across the resistor R_2. Equivalent resistance of the parallel connection of R_2 and galvanometer equals

$$R_{\|} = \frac{R_G \cdot R_2}{R_G + R_2};$$

and total resistance of the circuit is

$$R_{\|} + R_1 + r = \frac{R_G \cdot R_2}{R_G + R_2} + R_1 + r,$$

where r is internal resistance of the battery.

Current in the circuit can be found from Ohm's law to be

$$I = \frac{\varepsilon_1}{\dfrac{R_G \cdot R_2}{R_G + R_2} + R_1 + r}.$$

Here ε_1 is emf of the battery.

Thus, the voltage V across terminals of resistor R_2 equals

$$U = IR_{\|} = \frac{\varepsilon_1 R_{\|}}{\dfrac{R_G \cdot R_2}{R_G + R_2} + R_1 + r}.$$

This expression may be simplified taking into account that $r \ll R_1$, $R_2 \ll R_G$, to yield

$$U = \frac{\varepsilon_1 R_2}{R_2 + R_1}.$$

Finally, for galvanometer's graduation mark we have

$$C = \frac{\varepsilon_1 R_2}{(R_2 + R_1)N}. \tag{2.5}$$

Let us denote

$$\frac{\alpha}{C} = n, \tag{2.6}$$

then

$$n = \frac{N}{t^\circ - t_0^\circ}. \tag{2.7}$$

The quantity n is a deviation of galvanometer's pointer at 1°C difference of temperatures of soldered junctions of thermo-couple and is known as the sensitivity of thermo-couple.

If sensitivity n is known, the thermo-couple can be used as a thermometer. From equation (2.7) we have

$$t^\circ = \frac{N}{n} + t_0^\circ. \tag{2.8}$$

Then, if one soldered junction of thermo-couple is placed in the medium with unknown temperature t° and temperature t_0° of another junction is known, on the basis of galvanometer's reading and formula (2.8) one can calculate the unknown temperature.

3 PROCEDURE AND ANALYSIS

3.1 Determine emf of battery ε_1.

3.2 Assemble electric circuit as shown in figure 2.3.

3.3 Measure the galvanometer's deflection N at closed circuit and determine constant C by formula (2.5).

3.4 Disassemble the circuit.

3.5 Connect the galvanometer into thermo-couple's circuit as shown in fig. 2.2.

3.6 Note initial reading N_0 of the galvanometer (in initial state, both of soldered junctions have the same temperature).

3.7 Place one of the junctions to a thermostat filled with water of room temperature and the other junction to the container with water to be heated up.

3.8 Measure the room temperature t_0 by thermometer with 0.5°C accuracy.

3.9 By heating, increase the temperature $t_1°$ in container with water and note readings N_1 of galvanometer every 5°C until the water is boiling.

3.10 Fill out table 3.1 with results of experiment

Table 3.1

t_1, °C									
N_1									

3.11 Plot the galvanometer deflection N_1-N_0 versus difference of temperatures $t_1°$-$t_0°$ between junctions graphically.

3.12 Calculate the galvanometer sensitivity by formula (2.7). For this end take the maximum temperature difference from graph and corresponding value of $N = N_1 - N_0$.

3.13 Calculate the value of α by formula $\alpha = Cn$.

4 CONTROL QUESTIONS

1. Explain the processes which take place in junctions of metals.
2. Formulate the Volta laws.
3. What is Seebeck effect?
4. What is workfunction of metal?
5. What does a thermocouple consist of and how is it used in technics?

Experiment E6

EXAMINATION OF OHM’S LAW FOR ALTERNATING CURRENT

Objective: to examine Ohm’s law experimentally; to master methods of AC measurements.

1 EQUIPMENT

6) Inductor (coil);
7) capacitor;
8) AC ammeter and voltmeter;
9) two switches;
10) rheostat;
11) AC and DC sources.

2 THEORY

By definition, current is a flow of electric charge through the cross-section of a conductor. If this flow is constant in time, that is equal amounts of charge pass through the cross-section in equal time intervals, the current is known as direct current (DC). Otherwise the current is alternating (AC). Nowadays, in the power grid the alternating currents are used to provide the power to operate electrical appliances. A sinusoidal alternating current I can be described by formula

$$I = I_{\max} \sin(\omega t), \qquad (2.1)$$

where $I_{\max}$ is a maximum value of current, ω is an angular frequency and t is time.

A circuit consisting of a resistor, an inductor, and a capacitor connected in series, as shown in figure 2.1, is known as RLC circuit. Let us assume that the resistance of the resistor represents all the resistance in the circuit.

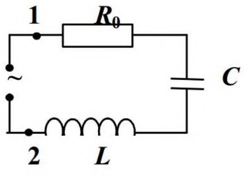


Figure 2.1

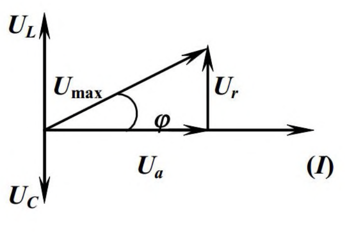


Figure 2.2

An instant value of voltage $\boldsymbol{U}$ across points 1 and 2 is a sum of voltage drops on the resistor $\boldsymbol{R_0}$, the capacitor $\boldsymbol{C}$ and the inductor $\boldsymbol{L}$, which also vary in time, but each voltage drop has some phase shift with respect to the current. Maximum value (amplitude) of voltage $\boldsymbol{U_{\max}}$ is determined by the vector diagram shown in figure 2.2, where following notations are introduced:

$$U_a = I_{\max} \cdot R, \qquad U_r = U_L - U_C,$$

$$U_L = I_{\max} \cdot \omega L, \quad U_C = I_{\max} \cdot \frac{1}{\omega C}.$$

First, we note that because the elements are in series, the current everywhere in the circuit must be the same at any instant. That is, the current at all points in a series AC circuit has the same amplitude and phase. The voltage across each element has a different amplitude and phase. In particular, the voltage across the resistor is in phase with the current, the voltage across the inductor leads the current by 90°, and the voltage across the capacitor lags behind the current by 90°, as it follows from figure 2.2.

In AC circuits that contain inductors and capacitors, it is useful to define the inductive reactance X_L and the capacitive reactance X_C as

$$X_L = \omega L,$$

$$X_C = \frac{1}{\omega C}.$$

Time-dependence of voltage is given by formula

$$U = U_{\max} \cdot \sin(\omega t + \varphi), \tag{2.2}$$

where φ is a phase shift between current and voltage,

$$U_{\max} = I_{\max} \cdot \sqrt{R^2 + (X_L - X_C)^2} = I_{\max} \cdot Z \tag{2.3}$$

is the maximum value of voltage.

Equation (2.3) is formally identical to Ohm's law and is known as Ohm's law for alternating current. Here

$$Z = \sqrt{R^2 + (X_L - X_C)^2} = \sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2} \tag{2.4}$$

is impedance of RLC-circuit, R is active resistance, $(X_L - X_C) = \left(\omega L - \frac{1}{\omega C}\right)$ is reactive resistance (reactance). One can examine the formula (2.4) by determination of ***Z*** in two independent ways: by formula (2.4) and from equation

$$Z = \frac{U_{rms}}{I_{rms}}, \tag{2.5}$$

where $\boldsymbol{I_{rms}}$ and $\boldsymbol{U_{rms}}$ are so called *rms* values of current and voltage. The notation *rms* stands for *root-mean-square*, which in this case means the square root of the mean (average) value of the square of the current or the voltage. Usually, AC ammeters and voltmeters are designed to read *rms* values.

The *rms* current and *rms* voltage in an AC circuit, in which the current follows formula (2.1), are given by the expressions

$$I_{rms} = \frac{I_{\max}}{\sqrt{2}} = 0.707 I_{\max}, \tag{2.6}$$

$$U_{rms} = \frac{U_{\max}}{\sqrt{2}} = 0.707 U_{\max}. \tag{2.7}$$

where $I_{\max}$ and $U_{\max}$ are the maximum values.

The average power delivered by the source in an RLC circuit is

$$P_{av} = I_{rms} U_{rms} \cos\varphi. \tag{2.8}$$

An equivalent expression for the average power is

$$P_{av} = I_{rms}^2 R. \tag{2.9}$$

The average power delivered by the source results in increasing internal energy in the resistor. No power loss occurs only in an ideal inductor or capacitor.

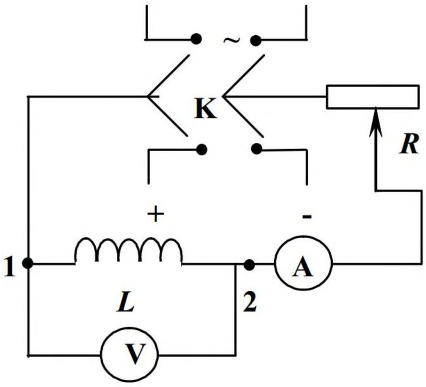


Figure 2.3

A diagram of the circuit designed for determination of impedance *Z,* inductance *L*, and capacitance *C* is given in Fig. 2.3. Here K denotes a switch used to connect a AC/DC source to the RLC circuit, rheostat, ammeter, inductance and voltmeter (connected in parallel to the inductance) are shown.

3 PROCEDURE AND ANALYSIS

3.1 Assemble electric circuit according to diagram shown in Fig. 2.3. In the first measurement, the coil ***L*** alone is connected to terminals 1 and 2. First, direct current source is used and DC voltage U_0 and current I_0 are measured. According to Ohm's law, resistance R_0 of the coil can be obtained as

$$R_0 = \frac{U_0}{I_0}.$$

3.2 Using the AC source, measure *rms*-voltage U_{rms} and *rms*-current I_{rms}. Calculate the total resistance of the inductor

$$R_1 = \frac{U_{rms}}{I_{rms}},$$

which takes into account both ohmic resistance R_0 of wire and inductance of the coil.

3.3 Calculate inductance of the coil by formula

$$L = \frac{\sqrt{R_1^2 - R_0^2}}{\omega};$$

here $\omega = 2\pi f$, where f is AC frequency (in Ukraine f=50 Hz).

3.4 Instead of the inductor ***L***, capacitor ***C*** is connected up. Using AC source, *rms*-voltage U_{rms} and *rms*-current I_{rms} are measured and capacitor's reactive resistance is calculated by formula

$$R_2 = \frac{U_{rms}}{I_{rms}}.$$

Capacitance *C* is calculated as

$$C = \frac{1}{\omega R_2}.$$

3.5Instead of the capacitor ***C***, series connection of inductor ***L*** and capacitor ***C*** is connected up**.** U_{rms} and I_{rms} are measured as before and impedance

$$Z_1 = \frac{U_{rms}}{I_{rms}}$$

of the ***LC***-segment is calculated.

3.6Substituting obtained values of R_0, L, C into formula

$$Z_2 = \sqrt{R_0^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}$$

theoretical estimation of impedance Z_2 is obtained. This estimation is to be compared with experimentally obtained Z_1 value.

3.7Experimental error for Z_1 is calculated as

$$\frac{\Delta Z_1}{Z_1} = \frac{\Delta U_{rms}}{U_{rms}} + \frac{\Delta I_{rms}}{I_{rms}},$$

where ΔU_{rms} and ΔI_{rms} are obtained using voltmeter's and ammeter's grades of accuracy, respectively.

3.8Fill out table 3.1 with results of measurements and calculations.

Table 3.1

U_0	I_0	R_0	U^L_{rms}	I^L_{rms}	R_1	L	U^C_{rms}	I^C_{rms}	R_2	C

U_{rms}	I_{rms}	Z_1	Voltmeter's grade of accuracy	Ammeter's grade of accuracy	ΔZ_1	Z_2

4. CONTROL QUESTIONS

1. What is alternating current? Write and explain a formula for sinusoidal current.
2. What are elements of RLC circuit? What phase shifts between voltage and current are observed on these elements?
3. Formulate Ohm's law for alternating current.
4. What are *rms* values for current and voltage?
5. What average power is delivered by the source in an RLC circuit?

Experiment O1

DETERMINATION OF WAVELENGTH BY DIFFRACTION GRATING

Objective: to investigate diffraction phenomena and determine the light wavelength with a diffraction grating.

1 EQUIPMENT:

1) optical bench with millimeter scale;
2) laser;
3) diffraction grating;
4) screen with millimeter scale.

2 THEORY

Diffraction is the phenomenon of light divergence from its initial line of travel. In general, diffraction occurs when waves pass through small openings, around obstacles, or past sharp edges, and penetrate into the shadow region. Waves of all kinds, including light and sound waves exhibit such property. The diffraction is always observed when obstacle's dimensions $\boldsymbol{a}$ are comparable with the wavelength $\boldsymbol{\lambda}$ (that is $\boldsymbol{a}\sim\boldsymbol{\lambda}$). For visible light the wavelengths belong to interval 0.4÷0.7 μm, so for the diffraction to be observed, the obstacles must be of the same order.

One can explain the phenomenon of diffraction by Huygens-Fresnel principle which states that every point of the wave front is the source of secondary wave and oscillation is a result of interference of secondary points. To determine the diffraction pattern one has to find interference maxima and minima by direct addition of secondary waves from all of the elements of wavefront, taking the amplitudes and phases into account.

Usually, diffraction is observed using the following layout. On the way of the light the opaque obstacle which obturates a part of wavefront is placed. Behind the obstacle a screen is installed. On the screen the diffraction pattern consisting of bright and dark fringes appears. One distinguishes two types of the phenomenon, Fraunhofer diffraction, which is realized in plane waves (parallel light beams) and Fresnel diffraction for spherical waves (divergent beams).

The diffraction grating, a useful device for analyzing light, consists of a large number of equally spaced parallel slits. A transmission grating can be made by cutting parallel lines on a glass plate with a precision ruling machine. The spaces between the lines are transparent to the light and hence act as separate slits. A reflection grating can be made by cutting parallel lines on the surface of a reflective material. The reflection of light from the spaces between the lines is specular, and the reflection from the lines cut into the material is diffuse. Thus, the spaces between the lines act as parallel sources of reflected light, like the slits in a transmission grating. Gratings that have many lines very close to each other can have very small slit spacings. For example, a grating ruled with 500 lines/mm has a slit spacing d = (1/500) mm = 2×10^{-3} mm. The best diffraction gratings have up to 1700 lines per 1 mm. For those gratings d~0,6 μm.

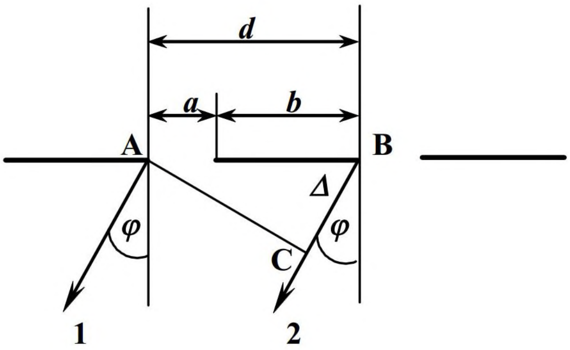


Figure 2.1

Let us derive the condition for diffraction maximum.

Consider an incident beam of the monochromatic light of wavelength λ, normal to the grating (fig. 2.1). In result of diffraction, light wave propagates in a variety of directions. We focus on the rays 1 and 2, at an angle φ to the grating. From ABC triangle one see, that the optical path difference of these rays is $\Delta = BC = (a+b)\sin\varphi = d\sin\varphi$, where $(a+b) = d$ is the period of gratings. If the path difference equals integer number of wavelengths, $\Delta = k\lambda$, with k=0,1,2,..., then one observes maximum at angle φ.

Finally, the condition of the diffraction maximum for the diffraction grating (known as diffraction grating formula) is

$$\boxed{d\sin\varphi = k\lambda}, \tag{2.1}$$

here k=0,1,2,… is an order of diffraction, $0\le\varphi\le\pi/2$.

At k=0 one has $\sin\varphi=0$ what corresponds to the bright central maximum. Orders $k=\pm1, \pm2, ...$ correspond to the symmetrically placed lateral maxima. Thus, the diffraction pattern appears to be a set of maxima (bright spots), symmetrically distributed around the central maximum, separated by wide dark regions.

The largest order of diffraction maximum k_{max} is obtained at condition, that the angle of light deviation is $\varphi=\pi/2$, and $\sin\varphi=1$. Then, from formula (2.1)

$$k_{max} = \frac{d}{\lambda}. \tag{2.2}$$

Obviously, k_{max} has to be an integer, then the fractional part of k_{max}, calculated by formula (2.2) is to be truncated. One can see that the number of the observed maxima is large for large d and small wavelength λ. The intensity of maxima decreases with increase of diffraction order k. The total number K of observable maxima (including the central one) is

$$K = 2k_{max} + 1. \tag{2.3}$$

It follows from the diffraction grating equation (2.1) that, at fixed d and k, the angle φ at which a maximum is observed depends on the wavelength λ. Therefore, maxima of different colors (corresponding to different λ) appear to be shifted one with respect to another (except the central maximum). For white light incident of the grating, in all maxima except of the central one a spectrum (iridescent coloring) is observed. That is why diffraction gratings are used in spectral instruments instead of prism. Diffraction gratings ensure higher spectral resolution, that is, allows to resolve spectral lines with close values of λ. For diffraction gratings resolution power is $\frac{\lambda}{\delta\lambda} = kN$, where λ is wavelength, $\delta\lambda$ is difference of wavelengths for close spectral lines, k is the diffraction order (number of the diffraction maximum), N is total number of slits in the grating.

In this laboratory experiment the diffraction grating is used for determination of the light wavelength.

The experimental apparatus is shown in Fig. 2.2. Along the optical bench **OB** in positions **P$_1$**, **P$_2$** and **P$_3$** the laser **L**, diffraction grating **DG** and screen **S** are installed, respectively. Both the optical bench **OB** and the screen **S are** provided with millimeter scales for measuring distances between DG and S and between diffraction maxima.

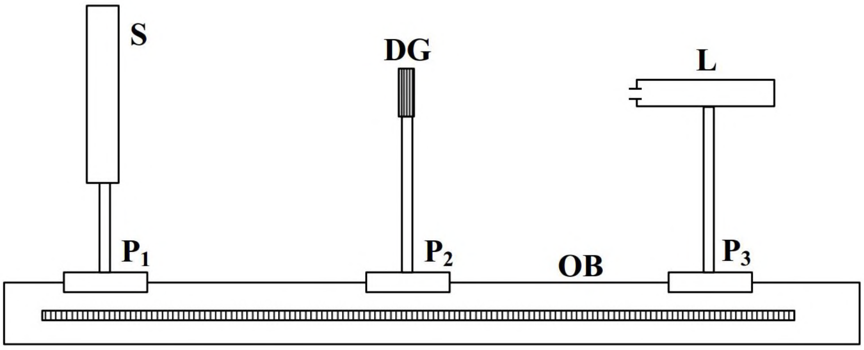


Figure 2.2

A beam of monochromatic light from laser **L** experiences the diffraction on grating **DG** and a set of light spots (diffraction maxima of different orders) are observed on screen **S**.

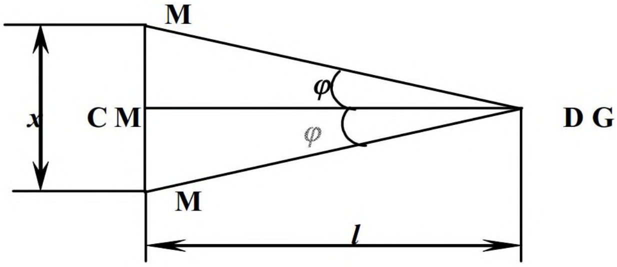


Figure 2.3

In Fig. 2.3, rays which produce symmetrically distributed maxima **M** on screen **S**, are shown. It is easy to see that

$$tg\varphi = \frac{x}{2l},$$

where ***x*** is distance between left and right maxima of the same order ***k***, symmetrical with respect to the central maximum **CM**., ***l*** is distance between **DG** and **S**. In practice, the angle φ is small, so $tg\varphi \approx sin\varphi$, and

$$sin\,\varphi = \frac{x}{2l}.$$

If the number of slits ***n*** per unit length is specified on the grating holder, then the grating constant equals

$$d = \frac{1}{n}.$$

By substitution of the above expression into formula (2.1) one obtains the computation formula

$$\lambda = \frac{xd}{2kl}, \qquad (2.4)$$

where λ is the wavelength, ***x*** is the distance between left and right maxima of the same order, ***k*** is the order of the diffraction maximum, ***l*** is distance between the grating and screen.

3 PROCEDURE AND ANALYSIS

1. Turn on the laser and direct the laser beam onto diffraction grating with known number of slits ***n*** per millimeter and calculate ***d=1/n***.
2. Adjust the diffraction pattern. Make it symmetrical with respect to the center of screen, installed on a distance ***l*** from the grating.
3. By a millimeter scale on the screen, measure the distance ***x*** between left and right maxima of the same order ***k***.
4. Calculate wavelength λ by formula (2.4).
5. Repeat the experiment for two different values of ***k*** and ***l***.
6. Calculate mean value of λ.
7. Estimate absolute and relative errors and compare the obtained result with table data for the light source used in experiment.
8. Fill the table 3.1 with the results of measurements and calculations.

Table 3.1

	d, 10^{-6} m	***k*** -	***l***, 10^{-3}, m	***x***, 10^{-3} м	λ, 10^{-9} m	$\Delta\lambda$, 10^{-9}, m	ε, %
1							
2							
3							
Mean value							

9. Represent the final result as

$$\lambda = (\lambda_{mean} \pm \Delta\lambda_{mean}) \text{ nm.}$$

4 CONTROL QUESTIONS

1. What is diffraction of light? What types of diffraction can be realized?
2. What is the diffraction grating? What are principal characterictics of a diffraction grating?
3. Write and explain diffraction grating formula.
4. What is difference of diffraction pattern for monochromatic light and white light?
5. Why a laser is used in this experiment as a source of light?

Experiment O2

DETERMINATION OF LIGHT WAVELENGTH USING NEWTON'S RINGS

Objective: determination of light wavelength from interference phenomenon.

1 EQUIPMENT:

1) photographic enlarger;
2) object-glass;
3) Newton's apparatus;
4) screen;
5) sheet of white paper;
6) pencil.

2 THEORY

Interference is the phenomenon which takes place at light waves superposition. As a result of interference, intensity of the resulting wave can be greater or less than the sum of individual waves, depending on the phase shift of the superposed waves. The waves must be coherent to enhance each other in some points (constructive interference) and cancel in other points (destructive interference). Coherent waves have the same frequency, constant phase shift and the same polarization. Throughout the interference pattern, energy of the wave is redistributed.

Phase shift of two waves created by the same source can be caused by the geometrical difference of paths passed by rays

$$\Delta r = r_2 - r_1,$$

where r_1 and r_2 are path lengthes of the first and the second waves, respectively. Optical difference of paths in a medium with refraction index (n>1)

$$\delta = \Delta r n = (r_2 - r_1)n = r_2 n - r_1 n,$$

where $r_1 n$ and $r_2 n$ are optical paths in the medium (the greater is refraction index, the slower the wave propagates through the medium and, effectively, the greater is the phase shift).

Passing from the less optically dense medium to the more optically dense one, in process of refraction on the boundary the wave accuires additional phase shift, equivalent to the loss of halfwavelength $\lambda/2$. This loss may be interpreted as the increase of the optical path by $\lambda/2$ and must be taken into account in calculation of optical difference δ.

Using the notion of path difference, we can find conditions for constructive and destructive interference. If the path difference is any even multiple of $\lambda/2$, then the phase angle is a multiple of 2π, phases of the waves coincide and the interference is constructive. For path differences of odd multiples of $\lambda/2$ the phases of the waves are shifted by $\pi/2$ and the interference is destructive.

Thus, we have the conditions for constructive interference (***maximum intensity***):

$$\delta = \pm m\lambda = 2m\lambda/2$$

and for destructive interference (***minimum intensity***):

$$\delta = \pm(m+1/2)\lambda = \pm(2m+1)\lambda/2$$

where δ is the optical path difference of the interfering beams of light; m=0,1,2... is a fringe order of interference for ***max*** or ***min***; λ is the wavelength.

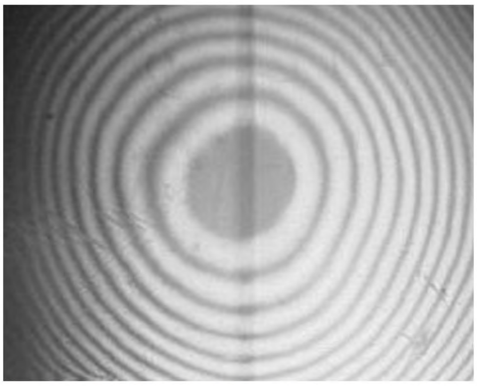


Figure 2.1. Newton's rings in reflected light.

In nature, interference is observed on thin films of soap, oil or petroleum on the surface of water. Newton's rings appear as a series of concentric, alternating light and dark rings formed due to interference between the light waves reflected from the top and bottom surfaces of the air film formed between the convex lens of large curvature and adjacent glass plate (Fig. 2.1). The light rings are caused by constructive interference between the light rays reflected from both surfaces, while the dark rings are caused by destructive interference. One can observe the Newton's rings in incident or reflected light. In our laboratory the interference pattern in incident light is realized.

Dark region can be observed in the center of the interference pattern in reflected light (see Fig.2.1). To explain this fact, one must take into account that one of two interfering waves has the phase shift of π due to reflection from plane of glass, though the geometric difference of paths is absent. Then, total optical path difference is $\delta = \lambda/2$. The pattern in incident light is always reverse to that of reflected light.

Let us consider a convex lens placed on top of a flat surface as an experimental setup and derive the formula for wavelength calculation from interference maximum condition.

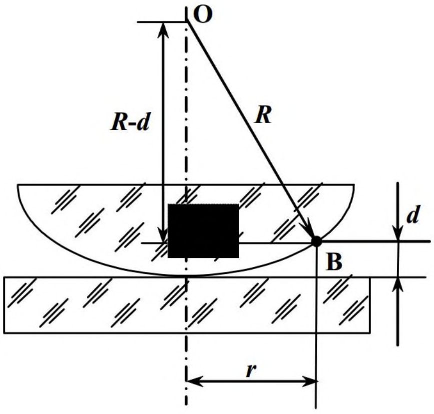


Figure 2.2

Difference of optical paths for *maximum* of intensity in reflected light is

$$\delta = 2d + \lambda/2,$$

and for incident light is

$$\delta = 2d + 2\lambda/2, \qquad (2.1)$$

where d is the thickness of the air film between the lens and the plate (see Fig. 2.2.). In our experiment we have incident light, so condition (2.1) is fulfilled for light rings. Consider triangle **OBM** where **OB**=$\boldsymbol{R}$ is the radius of curvature of the convex lens and **MB**=$\boldsymbol{r}$ is the radius of ring. For this triangle

$$\mathbf{OB}^2 = \mathbf{BM}^2 + \mathbf{MO}^2,$$

or

$$\boldsymbol{R}^2 = \boldsymbol{r}^2 + (\boldsymbol{R} - \boldsymbol{d})^2,$$

$$\boldsymbol{R}^2 = \boldsymbol{r}^2 + \boldsymbol{R}^2 - 2\boldsymbol{dR} + \boldsymbol{d}^2.$$

As we choose the lens of large curvature, $\boldsymbol{d} \ll \boldsymbol{R}$ and one may neglect $\boldsymbol{d}^2$. Then

$$2dR = r^2,$$

and

$$d = r^2/2R.$$

Now the value of ***d*** can be substituted into formula (2.1) to obtain

$$\delta = r^2 / R + 2\lambda / 2 .$$

From the interference condition we have for the maximum intensity:

$$\delta = (2m+1)\lambda / 2 ,$$

so that

$$r^2 / R + 2\lambda / 2 = (2m+1)\lambda / 2 .$$

Simplifying the above equation we obtain

$$r^2 / R = m\lambda - \lambda / 2 . \tag{2.2}$$

It is convenient to measure radii of two different rings r_i and r_k of the same color to calculate the wavelength. Then formula (2.2) for i^{th} and k^{th} rings is written as:

$$r_i^2 / R = (i - 1/2)\lambda , \tag{2.3}$$

$$r_k^2 / R = (k - 1/2)\lambda . \tag{2.4}$$

From equations (2.3) and (2.4) one has

$$r_i^2 - r_k^2 = (i-k)\lambda R ,$$

and, finally

$$\lambda = \frac{(r_i - r_k)(r_i + r_k)}{(i-k)R} . \tag{2.5}$$

3 DESCRIPTION OF EXPERIMENTAL APPARATUS

In the experimental setup a photo-enhancer is used. Optical arrangement is shown in Fig. 2.3. Light from the bulb lamp **L** passes through condensor **C** to the Newton’ apparatus **A**. Condensor forms a parallel light beam. Newton’s apparatus includes a convex lens of large curvature placed on top of a glass plate. Object-lens **O** projects the obtained Newton’s rings onto screen **S**. Distance between the Newton’s apparatus and object-lens is ***a***, ***b*** is the distance between the object-glass and screen.

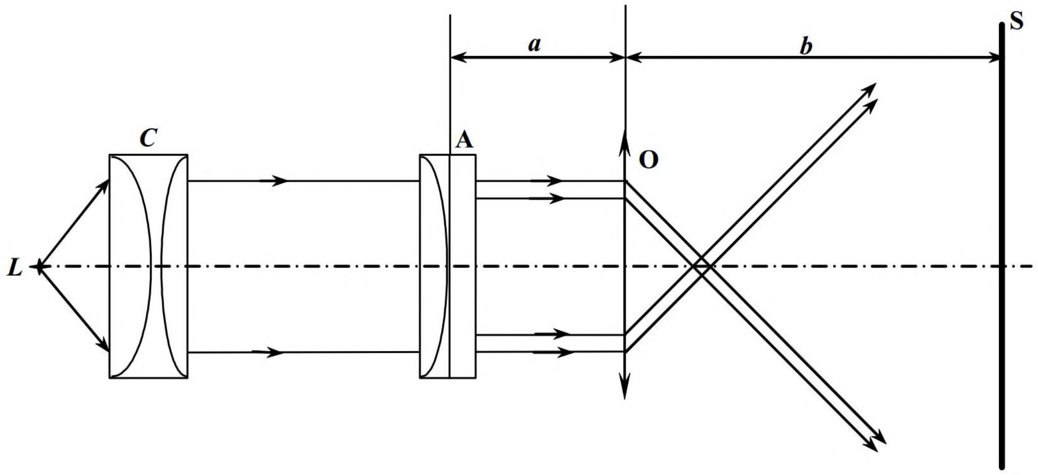


Figure 2.3

4 PROCEDURE AND ANALYSIS

4.1 Turn on the experimental apparatus. Obtain a clear image of Newton’s rings on the screen. Place a sheet of paper onto the screen and mark positions of intensity maxima of some color (red, for example) for a few rings (not less then five).

4.2Measure the radii of marked rings (note that these are observed rings, enlarged by the object-lens, but not actual ones).

4.3Calculate the radii r' of the actual rings by formula

$$r' = \frac{a}{b} r_n$$

where r_n is the radius of the ring observed on the screen, a is distance between the Newton's apparatus and object-lens, b is distance between the object-lens and screen.

Calculate the radii of four or five actual rings. Take pairs of r values and calculate 3 values of λ by formula (2.5). To attain an exact result it is reasonable to take r for rings as far one from another, as possible, for example, r_1 and r_5; r_2 and r_5; r_1 and r_4.

4.4Fill the tables 2.1 and 2.2 with the results of measurements and calculations.

Table 2.1

N	**1**	**2**	**3**	**4**	**5**
r_n, **mm**					
r'_n, **mm**					

Table 2.2

i	k	r_1, **mm**	r_k, **mm**	λ, **nm**	$\Delta\lambda$, **nm**	ε, **%**
Mean values						

4.5Estimate the absolute and relative errors.

4.6Represent the final result as

$$\lambda = (\lambda_{mean} \pm \Delta\lambda_{mean})\ \text{nm}.$$

4 CONTROL QUESTIONS

1. What is light interference?
2. What are conditions for minimum and maximum of interference?
3. What is called the Newton's interference apparatus.
4. Explain the construction of experimental apparatus?
5. What is the difference between interference patterns in monochromatic and white light?

Experiment O3

DETERMINATION OF STEFAN-BOLTZMAN CONSTANT

Objective: Study of thermal radiation. Determination of Stefan-Boltzman constant with use of pyrometer.

1 EQUIPMENT:

1) pyrometer;
2) voltmeter;
3) step-down transformer;
4) voltage regulator;
5) bulb lamp.

2 THEORY

Electromagnetic radiation of bodies at the expense of their internal energy is known as thermal radiation. Bodies radiate electromagnetic waves at arbitrary temperature but intensity and spectral composition of the radiation depends on the temperature substantially. At room temperature most of the radiation is in infrared part of the spectrum and hence is invisible.

Intensity of the thermal radiation is characterized by radiance $\boldsymbol{R_T}$. This quantity represents the energy, radiated from the unit surface area in a second. Radiance depends on a temperature, thus the thermal radiation allows body to be in thermal equilibrium with the surrounding: the more energy the body absorbs from the incident radiation, the higher its temperature rise, the more energy it emits and the equilibrium temperature is restored.

The radiant flux emitted from a unit area as waves with wavelengths in interval from $\boldsymbol{\lambda}$ to $\boldsymbol{\lambda+d\lambda}$ is known as the specific radiative intensity or spectral radiance, $\boldsymbol{r_{\lambda,T}}$. For any body the spectral radiance is proportional to its spectral absorption factor. Radiance and the specific radiative intensity are related

$$R_T = \int_0^\infty r_{\lambda,T} d\lambda . \qquad (3.1)$$

For real bodies, the reflected radiation is superposed with the radiated one. A convenient model for thermal radiation laws study is the blackbody, which reflects none of the incident waves. All of the incident electromagnetic radiation is absorbed by the blackbody, whatever the wavelength.

J.Stefan discovered in 1879 that the radiance of a blackbody is proportional to the fourth power of the black body's absolute temperature *T*. In 1884 L. Boltzmann, using thermodynamics, derived from theoretical considerations an expression

$$R_T = \sigma T^4 , \qquad (3.2)$$

where σ=5,67·10^{-8} W/(K^4·m^2) is the Stefan-Boltzmann constant. The equation (3.2) represents Stefan-Boltzmann law for blackbody radiation.

In 1900 M. Planck hypothesized that the electromagnetic waves are emitted and absorbed as discrete portions of energy (quanta), proportional to the wave frequency ν

$$\varepsilon = h\nu, \tag{3.3}$$

here **h**=6,625·10^{-34} J·s is Planck constant. On the basis of this hypothesis, M.Planck derived the formula for the spectral distribution of energy

$$r_{\lambda,T} = \frac{2\pi hc^2}{\lambda^5} \cdot \frac{1}{e^{hc/\lambda kT} - 1}, \tag{3.4}$$

here **c** is the speed of light, **k** is Boltzmann constant. After substitution of (3.4) into (3.1) one obtains (3.2). Formula (3.4) is also compliant with laws experimentally discovered for thermal radiation by M. Wien:

> the wavelength at which the spectral radiance $r_{\lambda,T}$ is maximal is inversely proportional to the absolute temperature (*Wien's displacement law*)

$$\lambda_{max} T = b, \tag{3.5}$$

here **b**=2,9·10^{-3} m·K;

> the maximal value of the spectral radiance $\boldsymbol{r_{\lambda,T}}$ is proportional to the fifth power of the absolute temperature (*Wien's second law*)

$$(r_{\lambda,T})_{\max} = cT^5, \tag{3.6}$$

where **c**=1,29·10^{-5} W/(m^3·K^5).

Spectral radiance of any (non-black) body can be represented as $\boldsymbol{e_T\, r_{\lambda,T}}$, where $\boldsymbol{e_T}$ is emissivity of the body. The emissivity is the ratio of the energy radiated by the given body to that of blackbody at the same temperature. Basing on equation (O3.2) for the radiance of a real body one obtains:

$$R_T = e_T \sigma T^4. \tag{3.7}$$

If the radiating body is placed into the medium of temperature $\boldsymbol{T_0}$, than formula (3.7) takes the form:

$$R_T = e_T \sigma \left(T^4 - T_0^4\right). \tag{3.8}$$

3 DERIVATION OF COMPUTATION FORMULA AND DESCRIPTION OF EXPERIMENTAL APPARATUS

In this experiment for the determination of Stefan-Boltzmann constant the power delivered to the incandescent lamp filament is compared with the radiant flux from its surface. The glowing of tungsten filament resembles the blackbody's ones. If energy losses are neglected, the electric power spent for the filament heating up can be equated to the energy radiated by filament in a unit of time:

$$IV = A\sigma\left(T^4 - T_0^4\right), \tag{3.9}$$

here **I** is current intensity, **V** is voltage across the lamp, **A** is total surface area of the filament.

From expression (3.9) one derives the computation formula

$$\sigma = \frac{IV}{A\left(T^4 - T_0^4\right)}. \tag{3.10}$$

Methods of distant objects temperature determination based on the thermal radiation laws, are known as optical pyrometry. Pyrometers, used for this purpose, can be of either radiation or optical (with disappearing filament). Radiation pyrometer allows to measure temperature by total thermal radiation of the body.

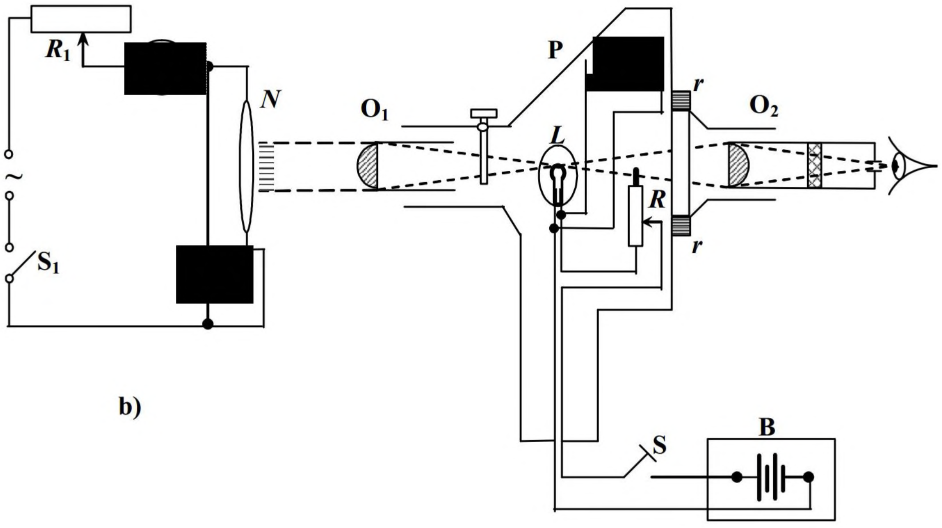


Figure 3.1

To measure the temperature of the glowing filament a radiation pyrometer can be used. Optical pyrometer with disappearing filament (fig. 3.1, a) is composed of optical system **P** with reference lamp ***L*** in the focal point. Optical system is focused on the light source (filament of bulb lamp ***N***). Using objective lens $\boldsymbol{L_1}$ the image of the glowing filament ***N*** is matched with the image of filament ***L***. The eyepiece $\boldsymbol{L_2}$ produces the enlarged image of both studied and reference filaments. Reference lamp ***L*** is powered by the source **B**. The incandescence is adjusted with rheostat ***R*** by the ring ***r***, placed on frontal part of the pyrometer. The aim of ***R*** adjustment is to set the equal incandecsences of filaments ***N*** and ***L.*** If this is attained, the image of reference filament ***L*** disappears against the image of filament ***N***. In this case the temperatures of both filaments are equal. Filament temperature is measured by reading of voltmeter $\boldsymbol{V_t}$, connected in parallel to reference lamp, with the scale graduated in degrees centigrade.

4 PROCEDURE AND ANALYSIS

4.1 Check connection of elements in circuit shown in Fig. 3.1.

4.2 Slowly increasing the voltage in primary circuit by regulator, make the incandescent filament ***N*** glowing (the filament should be dark red).

4.3 Focus the objective $\mathbf{O_1}$ of pyrometer of the filament ***N*** and obtain sharp image of it. Turn of the current in circuit of pyrometer lamp ***L***. Adjusting the eyepiece, obtain sharp image of the W-shape filament of pyrometer lamp ***L***.

4.4 Match images of filaments ***N*** and ***L.*** Varying the current in the pyrometer lamp equalize brightnesses of filaments ***N*** and ***L.*** Write down reading $\boldsymbol{t_V}$ by pyrometer scale $\boldsymbol{V_t}$, voltmeter $\boldsymbol{V_1}$ and galvanometer $\boldsymbol{A_1}$ readings.

4.5 Basing on the readings $\boldsymbol{t_V}$ of pyrometer scale and positive correction determined by nomogram (Fig. 3.2) one finds the actual temperature (in Celsius scale) of the incadenscent filament by formula $t_a = t_V + \Delta t$ and convert the result to Kelvin scale.

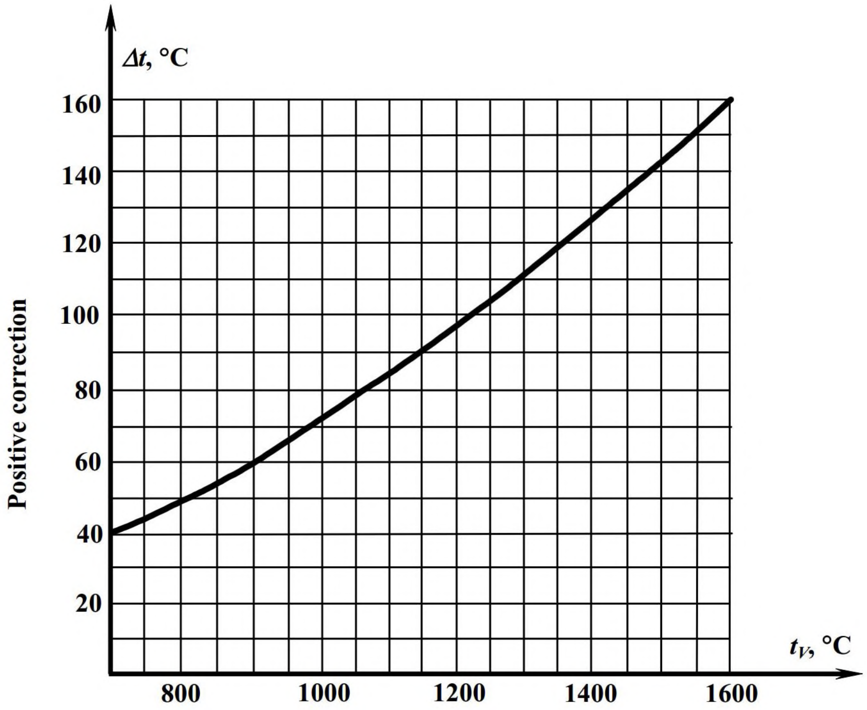


Figure 3.2

4.6 Fill the table 3.1 with the results of measurements and calculations

Table 3.1

	V, V	I, A	T_0, K	T, K	σ, $W/m^2 \cdot K^4$	$\Delta\sigma$, $W/m^2 \cdot K^4$	ε, %
1							▨
2							▨
3							▨
Mean values	▨	▨	▨	▨			

4.7 Calculate magnitude of Stefan-Boltzmann constant by formula (3.10).

4.8 Estimate the absolute and relative errors.

4.9 Represent the final result as

$$\sigma = (\sigma_{\text{mean}} + \Delta\sigma_{\text{mean}})\ W/(m^2K^4).$$

5 CONTROL QUESTIONS

1. What is the origin of thermal radiation?
2. What is a blackbody?
3. Formulate Stefan-Boltzman's law.
4. On the base of Wien's law, explain how radiation changes at increasing temperature.
5. Explain the principle of pyrometers operation.

Experiment O4

STUDY OF VOLTAGE-CURRENT CHARACTERISTIC AND SATURATION CURRENT OF EMISSION PHOTOTUBE

Objective: to master laws of photoemission, to obtain voltage-current characteristics and to determine saturation current for phototube.

1 EQUIPMENT

1) lighting chamber with scale ruler;
2) vacuum phototube;
3) light bulb of known luminous intensity;
4) electric power supply;
5) voltmeter;
6) ammeter.

2 THEORY

Photoelectric effect is the phenomenon in which electrons are ejected in surrounding by metals under external light. This phenomenon was first observed by H. Hertz in 1887. Photoemission is a manifestation of particle nature of a light and is explained by quantum theory of light, proposed by A.Einstein in 1905. According to quantum theory, light can be thought of as of the flow of photons (quanta of electromagnetic waves) with energies

$$\varepsilon = h\nu, \tag{2.1}$$

where h=6,625·10^{-34} J·s is Planck constant, ν is the frequency of light. In photoemission act a photon is absorbed by one of electrons in a matter so that photon disappears and the electron obtains all of its energy. Using a part of this energy the electron does a photoelectric work function W to go out of the matter. This work is needed to overcome electrostatic attraction of positively charged ions of matter. Quantitatively, photoelectric work equals the minimal energy sufficient to drive electron out of a solid. If $\varepsilon<W$, then photoemission does not occur because of lack of energy. If $\varepsilon=W$, photoemission starts. The frequency ν_0, or wavelength λ_0 of photon with energy equal to photoelectric work is expressed as $W = h\nu_0 = \frac{hc}{\lambda_0}$ ($\nu_0 = \frac{c}{\lambda_0}$, here c is speed of light in a vacuum). This frequency (or wavelength) is known as photoelectric threshold. If energy of a photon is greater then photoelectric work, $\varepsilon>W$, then the difference of energies $\varepsilon - W$ is transmitted to electron as kinetic energy.

Energy conservation law in photoemission act is expressed by Einstein equation of photoemission

$$h\nu = W + \frac{m\vartheta_{\max}^2}{2}, \tag{2.2}$$

where $h\nu$ is the energy of light quantum transmitted to electron, W is photoelectric work function, m is electron mass, $\vartheta_{\max}$ is maximal speed of outgoing electron, $\frac{m\vartheta_{\max}^2}{2}$ is maximal kinetic energy of photoelectron. Here the maximal kinetic energy of outgoing electron is taken because some electrons loose part of their energy in collisions with ions within substance on their way out.

Theory of Einstein explains the laws of photoemission discovered experimentally by Stoletov (1887-1889), Lenard and Thomson (1898):

1) maximum speed of photoelectrons is determined by the frequency of light and does not depend on intensity of the light;
2) saturation current is proportional to the magnitude of incident luminous flux;
3) for every metal there exists a minimal frequency ν_0 (photoelectric threshold), at which photoemission is still possible:

$$\nu_0 = \frac{W}{h}. \tag{2.3}$$

At $\nu < \nu_0$ there is no photoemission.

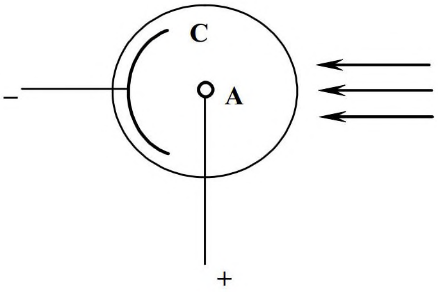


Figure 2.1

Photoemission is widely used in technology. Action of photoelectric cells and phototubes is based on the photoemission. Phototubes are used in electronic circuits of automatic control systems and for transmission of luminous energy into electric one. The simplest phototube is shown in fig. 2.1. It is a vacuumized glass tube, in which one half is covered with a thin metallic layer. This part is used as negatively charged cathode C. Anode **A** is made ring-shaped. Using the external power supply, one creates a voltage across the cathode and anode. If there is no external light, no current flows through the phototube, because there are no current carriers in vacuum inside.

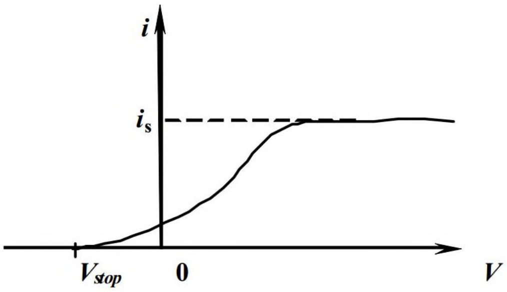


Figure 2.2

If there is external irradiation, in a phototube can exist a current, depending on voltage and incident light intensity. Dependence of photocurrent i on the voltage V across phototube at constant luminous flux is known as voltage-current characteristic of phototube. Such a characteristic is shown in Fig.2.2.

From Fig. 2.2 one can see that at some value of voltage, current reaches the saturation value and all electrons ejected from cathode fall on anode. The magnitude of saturation current i_s depends on the number of electrons ejected by cathode under light in time unit.

Current at negative potential is due to electron kinetic energy which allows them to reach anode even if anode repels them. To make the current equal zero, one has to apply a stopping (impedimental) voltage V_{stop} at which even the electrons with maximum energy can not reach the anode. One can write

$$\frac{m\vartheta_{\max}^2}{2} = eV_{stop}, \tag{2.4}$$

where ***e*** denotes charge of electron (elementary charge), V_{stop} is the stopping voltage. One can found the maximum value of photoelectron speed by measuring V_{stop}.

3 DESCRIPTION OF EXPERIMENTAL APPARATUS

Electric circuit for determination of voltage-current characteristics of vacuum phototube is given in Fig. 3.1. Power supply **E** after closing the key **k** feeds the phototube **P** and create voltage between cathode **C** and anode **A**. The voltage is measured by voltmeter **V**, photocurrent is measured by galvanometer **G**.

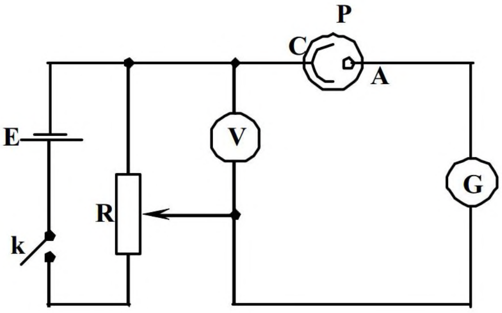


Figure 3.1

The phototube is placed into lighting chamber **CH** (see Fig. 3.2). In the same chamber there is a source of light, namely light bulb **O**. Position of the light bulb can be changed. The distance to phototube is measured by scale **S**. Voltage which feed the phototube is changed by regulator **R** and measured by voltmeter **V**. Photocurrent is measured by galvanometer **G**.

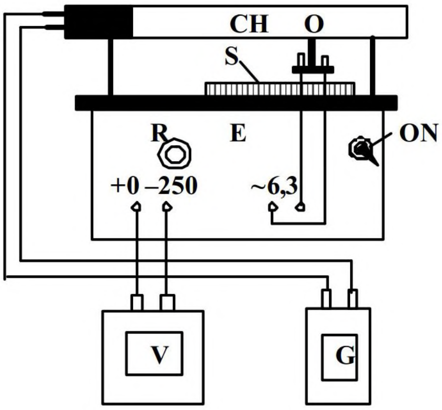


Figure 3.2

4 PROCEDURE AND ANALYSIS

4.1 Open the light-tight chamber and examine the phototube.

4.2 Set the light source on a distance specified by lab assistant and turn it on.

4.3 Close the chamber and, rotating the regulator R, change voltage across phototube. Every 10 volts measure photocurrent ***i*** by galvanometer. Fill out the table 4.1 with the results of experiment.

4.4 Repeat the measurement twice for different distances between the light bulb and phototube.

4.5 For all sets of data, plot voltage current characteristics graphically as dependences of current magnitude on voltage applied, in the same coordinate system.

Table 4.1

	l, cm	***V***, V	0	20	30	40	50	60	70	80	90	100
1		***i***, μA										
2		***i***, μA										
3		***i***, *μ*A										

5 CONTROL QUESTIONS

1. What is photoelectric effect?
2. Write down and explain Einstein formula for photoeffect.
3. Formulate laws of the photoeffect.
4. Explain the voltage-current characteristic of photoeffect. What is stopping potential?
5. Explain the principles of phototube operation.

Experiment O5

DETERMINATION OF SPECTRAL SENSITIVITY OF SEMICONDUCTING PHOTOCELL

Objective: to study the photoconductivity phenomenon and to estimate the spectral sensitivity of semiconducting photocell.

1 EQUIPMENT:

1) lightproof chamber with the studied photocell and a lamp;
2) light-filter set;
3) energy source;
4) microammeter.

2 THEORY

Photoresistor is a semiconducting device operated by the external light.

Photoconductivity is an additional conductivity of semiconductors caused by the increase of current carrier concentration under the action of light (as in photoelectric effect).

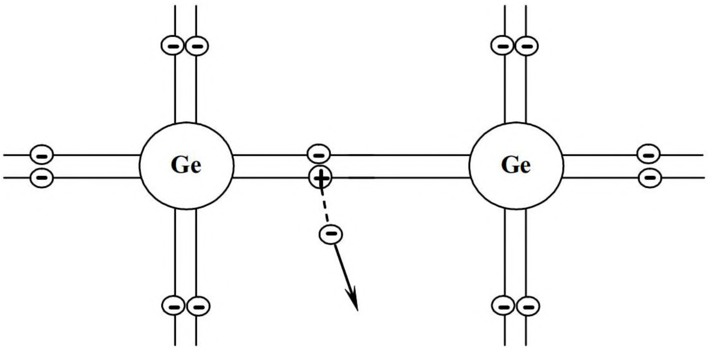


Figure 2.1

There are two types of conductance in semiconductors, the intrinsic conductance of pure semiconductors and the extrinsic conductance of the doped ones. In figure 2.1 the structure of the most widespread tetravalent semiconducting element, Germanium, is shown. In Germanium every atom is bind to every nearest neighbour by a valence bond in which one valence electron is localized (see fig. 2.1). The external electric field tends to move electrons but usually is too weak to break off the valence bonds. Electrons in semiconductor can move in the external electric field only if there are free valence bonds. In pure semiconductor these can be generated at increase of temperature or irradiation when an electron of valence bond moves away and leaves its position empty. In energy diagram every electron in a solid occupies an energy level inside an energy band. The highest filled band is called the valence band and the lowest unfilled band is known as the conduction band. When electron absorbs the energy of the external light or the energy of thermal vibrations of lattice it moves from its original level in valence band to the empty level in conduction band. In energy representation a conductance can be described as the transition of electrons to empty levels in the conduction band. The energy difference between the top of valence band and the bottom of conduction band is known as energy gap. No allowed energy states exist in the energy gap therefore to move an electron from valence band to conduction band the activation energy ΔE is to be supplied.

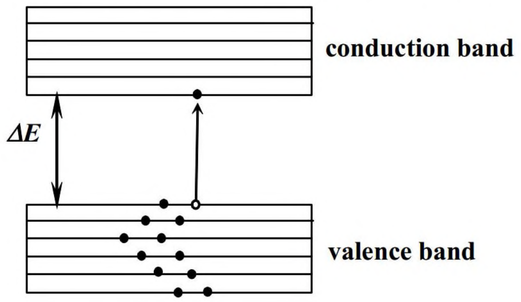


Figure 2.2

Since the valence band electrons that fill holes leave behind other holes, it is equally valid and more common to view the conduction process in the valence band as a flow of positive holes towards the negative electrode applied to a semiconductor. Thus, a pure semiconductor, such as Germanium or silicon, can be viewed in a symmetric way: pure semiconductor has equal numbers of mobile electrons in the conduction band and holes in the valence band. Furthermore, when an external voltage is applied to the semiconductor, electrons move toward the positive electrode and holes move toward the negative electrode.

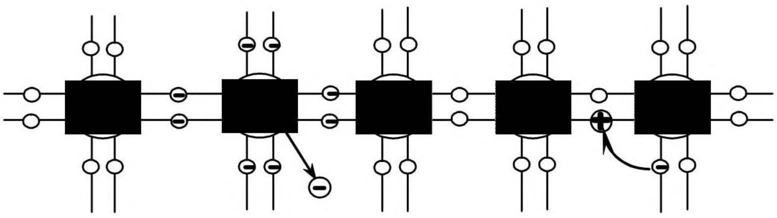


Figure 2.3

If some of atoms in Germanium matrix are substituted by atoms of pentavalent arsenic (As) then the fifth of valence electrons of As atom can be easily moved away as it is not used in valence bonding (see fig. 2.3). The energy cost ΔE_d of making As electrons mobile is much less than ΔE ($\Delta E_d << \Delta E$) and this can be explained by energy diagram shown in figure 2.4. Doping of Ge matrix with As atom creates an additional donor level in the energy gap of Germanium. This level lies much closer to the bottom of conduction band than the top of valence band thus valence electrons of arsenic require little addition energy to pass to the conduction band and become current carriers of ***n***-type (because of negative sign of electron charge). In this case no holes are created in the valence band, all conduction electrons are donated by the donor levels of a dopant. Likewise, doping with trivalent boron (B) atom creates hole in valence bond to which an electron from the neighbouring bond can pass (see figure 2.3). In energy diagram (fig. 2.4) it corresponds to occurrence of an acceptor level close to the top of conduction band.

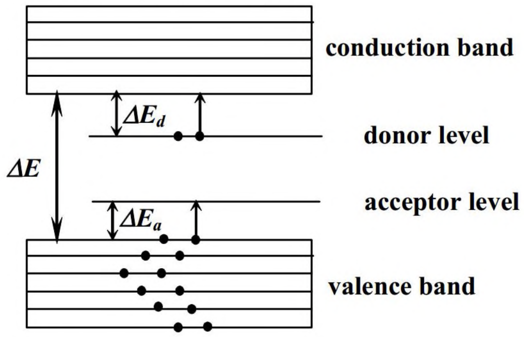


Figure 2.4

Passing to the acceptor level an electron leaves behind a hole which can be filled by another electron. In this way the hole becomes mobile without creating mobile electrons. This type of conductance is known as ***p***-type (with respect to the electronic background a hole is positively charged).

When light is absorbed by a material such as a semiconductor, the number of free electrons and electron holes changes and raises its electrical conductivity. To cause excitation, the light that strikes the semiconductor must have enough energy to raise electrons across the band gap, or to excite the impurities within the band gap. If a contact of ***n***- and ***p***-type semiconductors is irradiated by light then the contact potential difference (emf) occurs across the contact. The physical mechanism of this phenomenon is the following. Incident light photons release electrons from valence bonds. These electrons penetrate in the region of ***p***-type. As a result, ***n***-type region becomes electron-depleted and accumulates a positive electric charge and ***p***-region becomes electron-enriched and positively charged. The photovoltaic effect described above allows the transformation of light into electric energy and is widely used in photocells and photoresistors.

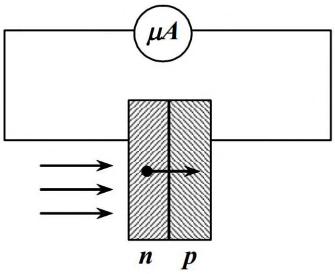


Figure 2.5

Varying the wavelength of the incident light with constant light intensity one observes that the photocurrent intensity depends on the wavelength. This dependence can be characterised by the spectral sensitivity which is determined as the ratio of the current to the luminous flux carried by light of spectral range from λ to $\lambda+d\lambda$:

$$\gamma_\lambda = \frac{i_\lambda}{\Phi_\lambda}. \tag{2.1}$$

The simplest way to measure the spectral sensitivity γ_λ of semiconducting photocell is to irradiate it with a monochromatic light and measure photocurrent i at known luminous flux as shown in figure 2.5. However light filters of monochromators have different transparency for different wavelengths so and in practice the flux Φ_λ would be dependent on λ. To overcome this complication one determines the flux on the basis of the known dependence $\Phi_\lambda = f(\lambda)$. Conversion factors K_λ are given in table 4.1.

For a monochromatic light the luminous flux is determined as

$$\Phi_\lambda = \frac{JS}{l^2}, \tag{2.2}$$

where S is photoelement area in m^2; J is light intensity in candelas; l is the distance from the light source to the photocell; $i_\lambda = K_\lambda \cdot i$; i is the photocurrent.

From the formulae (2.1) and (2.2) we obtain the computation formula for the sensitivity:

$$\gamma_\lambda = \frac{i_\lambda \cdot l^2}{JS}. \tag{2.3}$$

3 DESCRIPTION OF EXPERIMENTAL APPARATUS

Photocell (PC) and the lamp (**O**) (fig. 3.1), which is the light source, are placed into the chamber (C), preventing illumination of the photocell by the external light. When turning the lamp O on, in the circuit a current is induced due to the photocell illumination. The current is measured by microammeter (***μA***). On the way of the light beam incident on the photocell PC, the light filter F is placed, which blocks all the light except the particular wavelength.

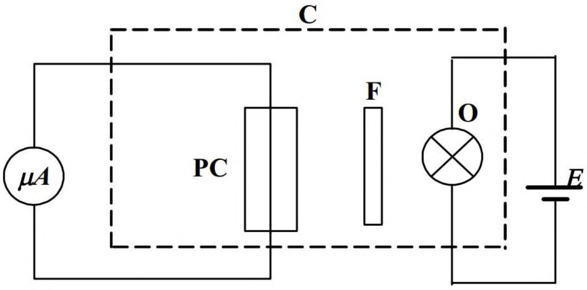


Figure 3.1

4 PROCEDURE AND ANALYSIS

4.1 Open the light-tight chamber and examine the photocell.
4.2 Set the lamp in a position specified by lab assistant and turn it on.
4.3 Changing the filters, illuminate the photocell with light of different wavelength.
4.4 Take the readings of microammeter (i) and calculate the value of iλ for every wavelength used.
4.5 Plot the dependence of iλ on λ.
4.6 For every wavelength used calculate the spectral sensitivity of the photocell γ_λ and plot γ_λ vs λ dependence.
4.7 Fill out table 4.1 with results of measurements and calculation:

Table 4.1

light filter	**λ, nm**	**K_λ**	**i, μA**	**i_λ,**	**γ_λ, μA /lm**
red		**1.12**			
orange		**1.06**			
yellow		**1.03**			
green		**0.96**			
blue		**0.92**			
violet		**0.89**			

Experiment O6

STUDY OF GAMMA ABSORPTION OF A MATTER USING THE GEIGER COUNTER

Objective: to learn radioactive decay law, to determine gamma absorption of lead

1 EQUIPMENT

1) Geiger counter of gamma-particles;
2) Lead plates;
3) Micrometer.

2 THEORY

Radioactivity is a spontaneous transformation of atomic nuclei. In these nuclear transformations chemical elements are transformed into other elements and high-energy particles can be emitted. The most widespread radioactive processes are

1. **alpha (*α*)** decay (nuclei of helium are emitted by matter),
2. **beta (*β*)** decay (electrons or positrons are emitted),
3. **gamma (*γ*)** decay (electromagnetic radiation of very short wavelength, 10^{-3} Å to 1 Å, are emitted).

These processes are also known as ionizing radiation. Ionizing radiation is either particle radiation or electromagnetic radiation in which an individual particle carries enough energy to ionize an atom or molecule by completely removing an electron from its orbit. Ionizing radiation is produced by radioactive decay, nuclear fission and nuclear fusion, by extremely hot objects (Sun, e.g., produces ultraviolet), and by particle accelerators.

Radioactivity was discovered by Henry Becquerel who studied uranium salts. Becquerel found that certain uranium salts are phosphorescent, that is, emit rays which expose photofilms. Two years later Pierre Curie and Marie Sklodowska-Curie discovered two radioactive elements, unknown before, namely raidum and polonium. In 1908 Ernest Rutherford discovered new radioactive gas, radon. All these elements are notable for their intensive radioactivity. Both natural and artificial radioactivity are described by radioactive decay law

$$N = N_0 e^{-\lambda \cdot t}, \qquad (2.1)$$

where N_0 is initial number of radioactive nuclei, N is number of nuclei after time t, λ is known as radioactive constant, characteristic to every chemical element. Time, in which half of initial number of nuclei transform, is known as half-life time. Half-life $T_{1/2}$ is related to λ:

$$T_{1/2} = \frac{\ln 2}{\lambda} = \frac{0{,}693}{\lambda}. \qquad (2.2)$$

Half-lives of chemical elements known today are in time range from $3 \cdot 10^{-7}$ s to $5 \cdot 10^{15}$ years.

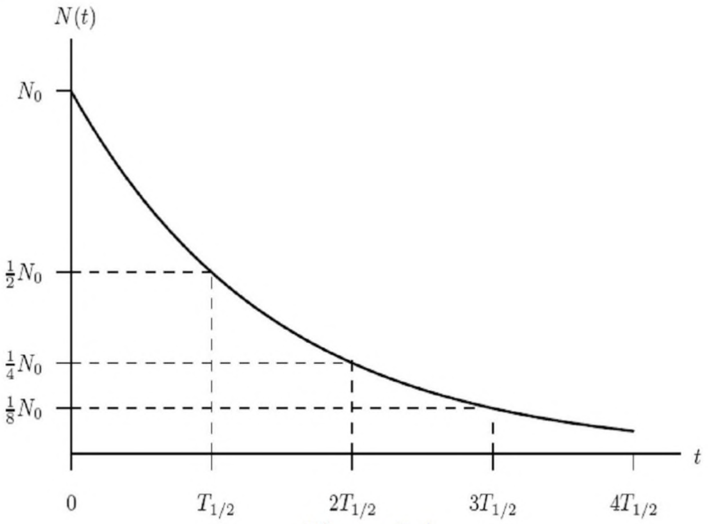


Figure 2.1

Mean lifetime τ of radioactive nucleus is a quantity inverse to radioactive constant

$$\tau = \frac{1}{\lambda}. \tag{2.3}$$

The law (2.1) is very accurate and is used, for example, to date fossil records. Carbon dating is based on the following principle. The isotope ${}^{14}_{6}C$ decays inside living bodies but is replenished from the air and food. Therefore, while an organism is alive, the concentration of this isotope in the body remains constant. After death, the replenishment from the breath and food stops, but the isotopes that are in the dead body continue to decay. As a result the concentration of ${}^{14}_{6}C$ in it gradually decreases. Therefore, by measuring the radioactive emissions from once-living matter and comparing its activity with the equilibrium level of emissions from things living today, an estimation of the time elapsed can be made.

Source activity is an important characteristic of a radioactive body. Activity is equal to number of decay acts per unit time. Source activity as proportional to radioactive constant and number of survived nuclei

$$\frac{dN}{dt} = -\lambda N. \tag{2.4}$$

1 Becquerel=1 decay per second is a unit of activity. Other widely used unit is 1 Curie $=3.700\times10^{10}$ decays per second.

Since they are able to penetrate through the matter, ionizing radiations are used for a variety of measuring methods. Here is the list of a few applications of radioactivity: radiography by means of gamma or X rays, gauges which use the exponential absorption law of gamma rays to indicate level of a substance in container or thickness of materials, detection of smoke, radioactive tracers for industry when the behavior of a certain chemical substance can be followed by tracing the radioactivity. Radiation is also useful in sterilizing medical hardware or food. Electrons, X rays or gamma rays may be used in radiation therapy to treat malignant tumors (cancer).

Nuclei, created in radioactive transformation, can be radioactive as well. Products of their transformations can be radioactive in their turn. This way radioactive families are formed. There are three natural radioactive families and one artificial. The natural ones are starting from uranium U^{238}, thorium Th^{232}, protactinium U^{235}. All the three end with isotopes of lead, Pb^{206}, Pb^{208} and Pb^{206}, respectively.

Alpha decay, in which nuclei of helium ${}_2He^4$ are emitted, are expressed by the following equation

$${}_ZX^A \rightarrow {}_{Z-2}Y^{A-4} + {}_2He^4. \tag{2.5}$$

Here X denotes the initial nucleus, Y denotes created fission fragment. As a rule, in alpha decay a few gamma-rays (photons of short wavelength) are created. Speed values of created $\boldsymbol{\alpha}$-particles are very high (of order of 10^7 m/s). Propagating through a matter, alpha particle looses most of its energy on ionization of molecules and atoms. The more dense the matter is, the less path will be covered by alpha particle. At normal conditions, $\boldsymbol{\alpha}$-particle's path in air is as long as a few centimeters, but only 10^{-6} m in solids.

In beta decay the initial nucleus emits or absorbs electron or its antiparticle, positron, in the following reaction

$${}_ZX^A \rightarrow {}_{Z+1}Y^A + {}_{-1}\boldsymbol{e}^0 + \tilde{\nu}. \tag{2.6}$$

Mass of an electron is about 2000 times less than mass of a nucleon (subatomic particle, proton or neutron), that is why mass of electron is taken to be zero in notation above. Neutral antineutrino $\tilde{\nu}$ is created together with electron and obtains a part of decay energy.

Reaction of positron decay can be written as

$$_{Z}X^{A} \rightarrow {}_{Z-1}Y^{A} + {}_{+1}e^{0} + \nu, \tag{2.7}$$

where $_{+1}e^{0}$ denotes positron, which has mass and charge magnitudes equal to those of an electron but charge of opposite sign, ν denotes neutrino.

In a process of electron capture a nucleus absorbs one of electron from atom's shell and one of protons p transforms into neutron n, emitting neutrino ν

$$_{1}p^{1} + {}_{-1}e^{0} \rightarrow {}_{0}n^{1} + {}_{0}\nu^{0}. \tag{2.8}$$

If the created nucleus has a surplus of energy (is in an excited state), the energy is emitted as gamma-quantum (a high-energy photon which has properties of both a particle and electromagnetic wave).

Absorption of ionizing gamma-radiation by a matter is described by the following equation (also known as absorption law)

$$I = I_0 e^{-\mu \cdot x}, \tag{2.9}$$

here I_0 is intensity of incident radiation, proportional to ionizing particles flow, I is the intensity inside the matter, after a distance x is covered by particles in the matter, μ is the linear coefficient of gamma absorption, which characterizes an ability of specific matter to interact with gamma-quanta. If the matter is a homogeneous one (composed of atoms of the same sort), it is reasonable to introduce mass coefficient of absorption $\mu_m = \mu/\rho$, where ρ is density of the matter.

3. DERIVATION OF COMPUTATION FORMULA

By comparing intensities of the ionizing particles flows before and after a metal plate

$$\frac{I}{I_0} = e^{-\mu \cdot x}, \tag{2.10}$$

one can determine absorption coefficient as

$$\mu = \frac{1}{x} \cdot \ln \frac{I_0}{I}. \tag{2.11}$$

Expression (2.11) is the calculation formula for this experiment.

4. DESCRIPTION OF EXPERIMENTAL APPARATUS

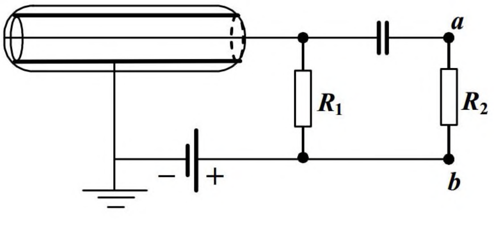


Figure 4.1

Although people cannot sense ionizing radiation, there is a range of simple, sensitive instruments capable of detecting amounts of radiation from natural and man-made sources. Ionizing radiation cause chemical reactions (chemical action), ionize atoms (ionizing action), stimulate luminescence of some substances (luminescent action). Accordingly, the detection methods may be classified as photochemical (photofilms and photoemulsions), ionizing (Geiger counter, cloud chamber, bubble chamber) and luminescent (scintillation counter). In the present experiment Geiger counter is used for detection of gamma radiation.

The counter consists of a thin metal cylinder (see Fig.4.1) filled with inert gas (usually helium, neon or argon with halogens added) at low pressure. A wire electrode runs along the center of the tube and is kept at a high voltage (above 2000 V) relative to the cylinder. When a particle passes through the tube, it causes ionization of the gas atoms and thus an electric discharge between the cylinder and the wire. The electric pulse can be counted by a computer or made to produce a click in a loudspeaker. The number of counts per second is proportional to intensity of the radiation.

5. PROCEDURE AND ANALYSIS

5.1 Put into operation the Geiger counter. Set it in regime of exposure dose determination.
5.2 Measure exposure dose due to background radiation three times and calculate the mean value. This value is to be subtracted from subsequent results for exposure dose.
5.3 Place a metal plate on the counter. Measure exposure dose three times and calculate the mean value.
5.4 Measure thickness of the used plate three times by micrometer and calculate the mean value.
5.5 Substitute the mean values into computation formula (2.11) and calculate the linear coefficient μ of gamma absorption.
5.6 Fill out the table 4.1 with results of measurements and calculations

Table 4.1

	I_{bg}	I_0	I	x 10^{-3} m	μ m^{-1}
1					▨
2					▨
3					▨
mean value					

6 CONTROL QUESTIONS

1. What is radioactivity?
2. What types of radioactivity do you know? Characterize alpha-, beta- and gamma decays.
3. Formulate laws of radioactive decay. What is half life time?
4. How does the ionizing radiation interact with matter? Explain the meaning of absorption coefficient.
5. Explain the principles of Geiger counter operation.

Appendix A. Tables

Table A.1 – Units of International System SI

Quantity and notation	Equation of definition	Unit of measurement	Abbreviation
1	**2**	**3**	**4**
Basic units			
Length ***l***	-	meter	m
Mass ***m***	-	kilogram	kg
Time ***t***	-	second	s
Thermodynamic temperature ***T***	-	kelvin	K
Amount of substance ***N*** N_ν	$N_\nu = \frac{m}{\mu} = \frac{N}{N_A}$	mole	mol
Electric current ***I***	-	ampere	A
Luminous intensity I_ν	-	candela	cd
Additional units			
Angle φ	$\varphi = \frac{L}{R}$	radian	rad
Solid angle Ω	$\Omega = \frac{S}{R^2}$	steradian	srad
Derived units			
Area ***A***	$S = l^2$	square meter	$м^2$
Volume ***V***	$V = l^3$	cubic meter	$м^3$
Frequency ν	$\nu = \frac{1}{T}$	Hertz	$Hz=s^{-1}$
Angular velocity ω	$\omega = \frac{\Delta\varphi}{\Delta t}$	radian per second	rad/s
Angular acceleration ε	$\varepsilon = \frac{\Delta\omega}{\Delta t}$	radian per square second	rad/s^2
Velocity (speed) ϑ	$\vartheta = \frac{\Delta l}{\Delta t}$	meter per second	m/s
Acceleration ***a***	$a = \frac{\Delta\vartheta}{\Delta t}$	meter per square second	m/s^2
Density ρ	$\rho = \frac{m}{V}$	kilogram per cubic meter	kg/m^3
Force ***F***	$F = ma$	Newton	N
Pressure ***P***	$P = \frac{F}{S}$	Newton per square meter (Pascal)	$N/m^2=Pa$
Mumentum ***p***	$p = m\vartheta$	kilogram-meter per second	kg·m/s

Continuation of table A.1

1	2	3	4
Moment of inertia $\boldsymbol{I}$	$I = mr^2$	kilogram-square meter	$kg{\cdot}m^2$
Torque $\boldsymbol{\tau}$	$\tau = Fl$	Newton-meter	N·m
Angular momentum $\boldsymbol{L}$	$L = I\omega$	kilogram-square meter per second	$kg{\cdot}m^2/s$
Work (energy change) $\boldsymbol{W}$	$W = F \cdot s \cdot \cos\alpha$	Joule	J
Power $\boldsymbol{P}$	$P = \frac{W}{t}$	Watt	W
Heat $\boldsymbol{Q}$	$Q = m \cdot c \cdot \Delta T$	Joule	J
Specific heat $\boldsymbol{c}$	$c = \frac{Q}{m\Delta T}$	Joule per kilogram-Kelvin	J/(kg·K)
Molar specific heat $\boldsymbol{C}$	$C = \frac{Q}{\frac{m}{\mu}\Delta T}$	Joule per mole-Kelvin	J/(mole·K)
Surface tension $\boldsymbol{\alpha}$	$\alpha = \frac{F}{l}$	Newton per meterp	N/m
Linear coefficient of thermal expansion $\boldsymbol{\alpha_l}$	$\alpha_l = \frac{\Delta l}{l\Delta T}$	Kelvin to the minus one power	K^{-1}

Table A2. Fundamental Physical Constants

Constant	Symbol	Numerical value
Avogadro's number	$\boldsymbol{N_A}$	6.022×10^{23} $mole^{-1}$
Boltzman's constant	$\boldsymbol{k}$	1.38×10^{-23} J/K
Faraday constant	F	9.64853415(39) x 10^4 C· mol^{-1}
Electric constant	ε_0	8.854187817 x 10^{-12} $F{\cdot}m^{-1}$
Magnetic constant	μ_0	4π x 10^{-7} $H{\cdot}m^{-1}$
Speed of light in vacuum	c	299792458 $m{\cdot}s^{-1}$
Planck's constant	$\boldsymbol{h}$	6.625×10^{-34} J·s
Stefan-Boltzman's constant	$\boldsymbol{\sigma}$	5.67×10^{-8} $W/(m^2{\cdot}K^4)$
Rydberg's constant	$\boldsymbol{R'}$	3.2931193×10^{15} s^{-1}
Electron mass	m_e	$9.10938188(72)\times10^{-31}$ kg
Elementary charge	e	$1.602176462(63)\times10^{-19}$ C
Atomic unit of mass and the corresponding energy	**a.m.u.**	1.660×10^{-27} kg; 931 MeV = 1.49×10^{-10} J
Mass and rest energy of proton	$\boldsymbol{m_p}$	1.6726×10^{-27} kg; 938.3 MeV
Mass and rest energy of neutron	$\boldsymbol{m_n}$	1.675×10^{-27} kg; 939.6 MeV

Source:
CODATA Recommended Values of the Fundamental Physical Constants: 1998,
by Peter J. Mohr and Barry N. Taylor, National Institute of standards and Technology,
Gaithersburg, MD 20899-8401, http://physics.nist.gov/PhysRefData

Table A.3 – Densities of solids (at 20°C), kg/m^3

Solid	Density	Solid	Density
Diamond	3511	Copper	8960
Graphite	2100-2520	Steel	7700-7900
Concrete	1800-2400	Iron	7900
Wood:		Cast iron:	
oak	700-1000	wrought iron	7200-7700
pine-tree	400-700	grey iron	6600-7400
Aluminium	2700	Lead	11350

Table A.4 – Elastic constants for solids

Material	Young modulus, GPa	Shear modulus, GPa
Aluminium	63-70	25-26
Rubber	0.008	0.003
Copper	82	-
Nickel	204	79
Steel	206	80
Cast iron	113-116	44

Table A.5– Viscosity coefficients η of gases and liquids

Gas	t, °C	η, μPa·s	Liquid	t, °C	η, Pa·s
Nitrogen	0	16.5	Water	10	0.001307
Hydrogen	0	8.5		15	0.001140
Helium	0	18.8		20	0.001005
Oxygen	0	19.2	Glycerin	-20	134
				0	12,1
				20	1.5
Air	0	17.1	Liquid nitrogen	-196	158
	20	18.1	Gasoline	20	530
	100	21.2	Ethyl alcohol	20	1190

Table A. 6 – Surface tension of distilled water and ethyl alcohol at various temperatures (α, µN/m)

Liquid	Temperature, °C			
	0	30	60	90
Water	75.6	71.18	66.18	60.75
Ethyl alcohol	24.4	21.9	19.2	16.4

Table A. 7 – Specific heat of gases at normal pressure (c_p, kJ/(kg·K))

Temperature, °C	Oxygen		Air		Carbonic acid		Water vapor		Ethyl alcohol vapor	
	c_p	γ	c_p	γ	c_p	γ	c_p	γ	c_p	γ
0	0.9149	1.397	1.006	1.400	0.8148	1.301	-	-	1.341	1.16
100	0.934	1.385	1.010	1.397	1.9136	1.260	1.103	1.28	1.689	1.12
200	0.964	1.37	1.027	1.390	0.9927	1.235	1.978	1.30	2.011	1.10
300	0.9948	1.353	1.048	1.378	1.057	1.217	2.015	1.29	2.321	1.08
600	1.069	1.321	1.115	1.345	1.192	1.188	2.208	1.26	3.168	1.06

Table A.8 – Linear coefficient of thermal expansion α of solids

Solid	t, °C	α, 10^{-6} °C^{-1}	Solid	t, °C	α, 10^{-6} °C^{-1}
Aluminium	0-200	24.5	Silver	0-200	19.8
	0-600	27.9		0-900	22.4
Iron	0-100	12.2	Brass	20-100	17.8
	0-800	14.8			
Copper	0-200	17.4	Stainless steel	20-200	11.1
	0-1000	20.3			
Lead	0-300	31.3	Cast iron Grey iron	20-700 20-500	12.8 10.5

Table A9. Resistivity and Temperature Coefficient at 20 C

Material	Resistivity ($\Omega\cdot$m)	Temperature coefficient per degree C
Silver	$1.59\cdot10^{-8}$	0.0061
Copper	$1.68\cdot10^{-8}$	0.0068
Aluminum	$2.65\cdot10^{-8}$	0.00429
Tungsten	$5.6\cdot10^{-8}$	0.0045
Iron	$9.71\cdot10^{-8}$	0.00651
Platinum	$10.6\cdot10^{-8}$	0.003927
Lead	$22\cdot10^{-8}$	...
Mercury	$98\cdot10^{-8}$	0.0009
Nichrome (Ni,Fe,Cr alloy)	$100\cdot10^{-8}$	0.0004
Constantan	$49\cdot10^{-8}$	...
Carbon (graphite)	$(3\text{-}60)\cdot10^{-5}$	-0.0005
Germanium	$(1\text{-}500)\cdot10^{-3}$	-0.05
Silicon	0.1-60	-0.07
Glass	$(1\text{-}10000)\cdot10^{9}$	...
Quartz (fused)	$7.5\cdot10^{17}$	...
Hard rubber	$(1\text{-}100)\cdot10^{13}$	...

Table A10. Absolute refraction indices *n* (for wavelength λ=589.3 nm)

Substance	***n***	**Substance**	***n***
Solids		**Liquids**	
Diamond	2.42	Water	1.33
Beryl	1.58	Glycerine	1.47
Rock salt	1.54	Canada turpentine	1.53
Crystalline quartz	1.54	Castor oil	1.48
Fused quartz	1.46	Cedar oil	1.52
Corundum (Ruby)	1.77	Sunflower seed oil	1.47
Ice	1.31	Liquid paraffin	1.48
Plexiglass	1.50	Hydrogen sulfide	1.63
Sugar	1.56	Turpentine	1.47
Glass (heavy flint)	1.80	Methyl alcohol	1.33
Glass (light crown)	1.57	Ethyl alcohol	1.36
Tourmaline	1.67	Toluene	1.50
Iceland spar	1.66	Ethylic ether	1.35

Table A11. Illuminance from different light sources

Light source	Illuminance, lx
Sunlight at noon in summer	10^5
Sunlight at noon in winter	10^4
Cloudy sky in summer	$5\times10^3 - 2\times10^4$
Cloudy sky in winter	$10^3 - 2\times10^3$
Reading lamp	50 – 200
Full Moon	0.2
Sky in a moonless night	$3\cdot10^{-4}$

Table A12. Critical angles of total internal refraction.

Substance	i_{tot}, °	Substance	i_{tot}, °
Water	49	Hydrogen sulfide	38
Glicerine	43	Glass (heavy flint)	34
Glass (light crown)	40	Diamond	24

Table A13. Workfunctions and threshold frequencies for metals

Substance	W, eV	λ, nm
Cuprous oxide	5.15	250
Silver bromide	3.7 – 5.14	335 – 240
Sodium	2.10	590
Cesium	1.36	909
Barium	1,1	1130

Table A14. Mass coeficients of X rays absorption, 10-1 m2/kg

Wavelength, nm	Al	Fe	Cu	Pb
0.02	0.27	1.06	1.45	4.6
0.06	3.3	23.5	32	77
0.10	14.0	95	134	77
0.16	55	390	60	258
0.20	106	78	119	–

Table A15. Masses of isotopes (a.m.u.)

Isotope	Mass	Isotope	Mass	Isotope	Mass
$_{1}H^{1}$	1.00814	$_{4}Be^{9}$	9.01505	$_{14}Si^{30}$	29.98325
$_{1}H^{2}$	2.01474	$_{5}B^{10}$	10.01612	$_{20}Ca^{40}$	39.97542
$_{1}H^{3}$	3.01700	$_{6}C^{12}$	12.00380	$_{27}Ca^{56}$	55.975769
$_{2}He^{3}$	3.01699	$_{7}N^{13}$	13.00987	$_{29}Cu^{63}$	62.94962
$_{2}He^{4}$	4.00388	$_{7}N^{14}$	14.00752	$_{48}Cd^{113}$	112.94206
$_{3}Li^{6}$	6.01703	$_{8}O^{17}$	15.9994	$_{80}Hg^{200}$	200.02800
$_{3}Li^{7}$	7.01823	$_{12}Mg^{23}$	23.00145	$_{92}U^{235}$	235.11750
$_{4}Be^{7}$	7.01916	$_{12}Mg^{24}$	23.98504	$_{92}U^{238}$	238.12376
$_{4}Be^{8}$	8.00785	$_{13}Al^{27}$	26.98154		

Table A16. Half-life times of isotopes

$_{20}Ca^{45}$	164 days
$_{88}Sr^{90}$	28 years
$_{84}Po^{210}$	138 days
$_{86}Rn^{222}$	3,82 days
$_{88}Ra^{226}$	1590 years
$_{92}U^{235}$	7.1×10^{8} years
$_{92}U^{238}$	4.5×10^{9} years

Table A17. Notation conventions

A device of moving-coil system with moving loop	
Iron coil device	
Electrodynamic device	
Induction system device	
Vibration system	
Electrostatic system	
Flash testing voltage 2 kV	
Electrostatic screen	
Magnetic screen	○
Grounding clamp	⏚
Corrector	
Accuracy class, %,	**1,5**
One-phase alternating current	~
Direct current	—
Direct and alternating current	≂
Three-phase alternating current	≋
Horizontal operational position	⊓
Vertical operational position	⊥
Operational position at the angle 60°	**∠60°**

Appendix B. Laboratory reports

After completing measurements and calculations, students can opt for preparing reports on their laboratory activity. Having in mind that the main goals of laboratory sessions are to master theoretical concepts and to gain experimental skills, the report should be prepared after a thorough study of a corresponding theory chapter, having all activities of particular experiment done.

In following pages, blank reports tables are printed to facilitate preparation of report papers. Within the report, all experimentally measured data have to be given and the final result is to be represented in the standard form, taking into account rounding conventions and scientific notation rules. Report papers are then detached and submitted to instructor.

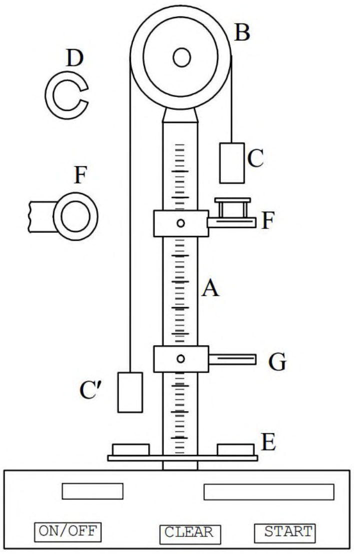
Before submission of the report, student is to prepare for answering control question, though discussion is not limited to the questions listed in this manual, these are rather examples of questions to be asked by instructor. Practical issues, as experimental error estimation and possible measures and improvements for accuracy improvement can also be discussed. If the determination of a physical constant was an objective for the experiment, the obtained value is to be compared with precise table value or interval of confidence for the value, discrepancies should be analysed and sources of error revealed.

Student's name ____

Laboratory report M1

STUDY OF TRANSLATIONAL MOTION LAWS WITH ATWOOD MACHINE

Objective of the experiment: Study of the translation motion laws for a rigid body. Determination of translation motion acceleration.



EQUIPMENT

1. Experimental apparatus (Atwood machine).
2. Two identical weights bound together by a cord.
3. Set of different mass rings.

COMPUTATION FORMULAS

$$a_1 = \frac{S_2^2}{2S_1t_2^2}$$

$$a_2 = \frac{m_1}{2m+m_1}g$$

N	S_1 10^{-3} m	ΔS_1 10^{-3} m	S_2 10^{-3} m	ΔS_2 10^{-3} m	t_2 s	Δt_2 s	a, m/s²	Δa m/s²	ε %
1			▨	▨			▨	▨	▨
2									
3									
Mean value									

m 10^{-3} kg	Δm 10^{-3} kg	m_1 10^{-3} kg	Δm_1 10^{-3} kg	g m/s²	Δg m/s²	a, m/s²	Δa m/s²	ε %

Student's name ____

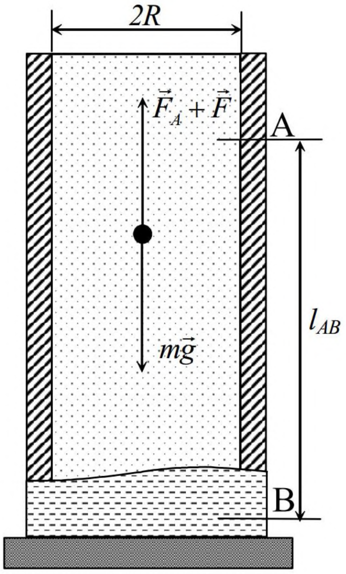
Laboratory report M2

DETERMINATION OF LIQUID VISCOSITY BY STOCKES METHOD

Objective of the experiment: To master the basic concepts of fluid mechanics and to determine the dynamic coefficient of viscosity for a liquid.

EQUIPMENT

1. Stockes' apparatus.
2. Metallic ball.
3. Micrometer.
4. Vernier caliper.
5. Stop-watch.



COMPUTATION FORMULA

$$\eta = \frac{1}{18}\frac{d^2(\rho_b - \rho_L)gt}{l_{AB}(1 + 2{,}4\frac{d}{D})}$$

N	d, 10^{-3} m	Δd, 10^{-3} m	ρ_c, $10^3 \cdot \frac{\text{kg}}{\text{m}^3}$	$\Delta\rho_c$, $10^3 \cdot \frac{\text{kg}}{\text{m}^3}$	ρ_r, $10^3 \cdot \frac{\text{kg}}{\text{m}^3}$	$\Delta\rho_r$, $10^3 \cdot \frac{\text{kg}}{\text{m}^3}$	t, s	Δt, s	D, 10^{-3} m	ΔD, 10^{-3} m
1			▨	▨	▨	▨	▨	▨		
2										
3										
Mean value										

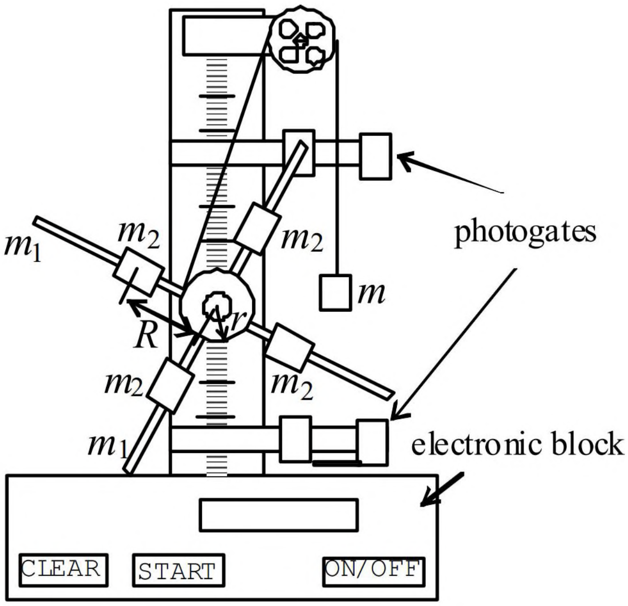
N	l_{AB}, 10^{-2} m	Δl_{AB}, 10^{-2} m	g, m/s^2	η, Pa·s	$\Delta\eta$, Pa·s	ε, %
1	▨	▨	▨	▨	▨	▨
2						
3						
Mean value						

Student's name ____

Laboratory report M3

STUDY OF ROTATIONAL MOTION OF RIGID BODY ON OBERBECK PENDULUM

Purpose of the experiment: to master the basic concepts of kinematics and dynamics of rigid body rotational motion and to determine the Oberbeck pendulum moment of inertia for.



EQUIPMENT

1. Oberbeck pendulum.
2. Millimeter scale.
3. Stop-watch.
4. Vernier caliper.

COMPUTATION FORMULAS

$$I=\frac{1}{6}m_1l^2+4m_2R^2$$

$$I=\frac{md^2}{4}\left(\frac{gt^2}{2h}-1\right)$$

m_1, 10^{-3}kg	Δm_1, 10^{-3}kg	l, 10^{-3} m	Δl, 10^{-3} m	m_2, 10^{-3}kg	Δm_2, 10^{-3}kg	R, 10^{-3}m	ΔR, 10^{-3}m	I, 10^{-2} kg·m^2	ΔI, 10^{-2} kg·m^2	ε, %

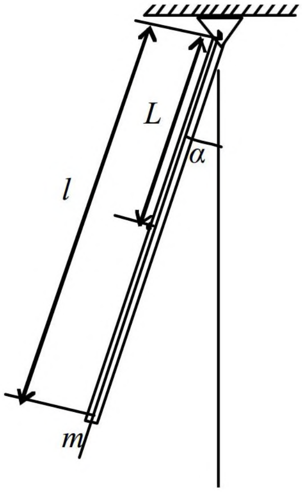
N	m, 10^{-3} kg	Δm, 10^{-3} kg	d, 10^{-3} m	Δd, 10^{-3} m	t, s	Δt, s	h, 10^{-3} m	Δh, 10^{-3} m	I, 10^{-2} kg·m^2	ΔI, 10^{-2} kg·m^2	ε, %
1	▨	▨							▨	▨	▨
2											
3											
Mean value											

Student's name ____

Laboratory report M4

DETERMINATION OF GRAVITY ACCELERATION BY METHOD OF PHYSICAL PENDULUM

Purpose of the experiment: to study oscillations of the physical pendulum; to determine free fall acceleration by method of physical pendulum.



EQUIPMENT

1. Physical pendulum.
2. Milimeter scale.
3. Stop-watch.

COMPUTATION FORMULA

$$g = \frac{8\pi^2}{3} \cdot \frac{l}{T^2}$$

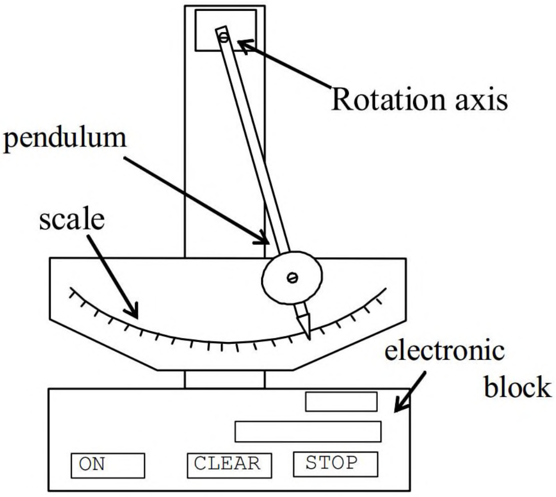
	l, m	**Δl, m**	**T, s**	**ΔT, s**	**g, m/s^2**	**Δg, m/s^2**	**ε, %**
1							
2							
3							
Mean value							

Student’s name ____

Laboratory report M5

DETERMINATION OF LOGARITHMIC DECREMENT AND DAMPING COEFFICIENT OF OSCILLATIONS

Purpose of of the experiment: to master the basic concepts of theory of oscillations. To determine logarithmic decrement and damping coefficient.



EQUIPMENT

1. Pendulum with a scale.
2. Stop-watch.

COMPUTATION FORMULAS

$$\beta = \frac{1}{nT}\ln\frac{A_1}{A_2} = \frac{1}{t}\ln\frac{A_1}{A_2}$$

$$\lambda = \beta T = \frac{1}{n}\ln\frac{A_1}{A_2}$$

	n	t, c	Δt, c	A_1, …°	ΔA_1, …°	A_2, …°	ΔA_2, …°	β, c^{-1}	$\Delta\beta$, c^{-1}	ε_β %	λ	$\Delta\lambda$	ε_λ %
1										▨			▨
2										▨			▨
3										▨			▨
Mean value													

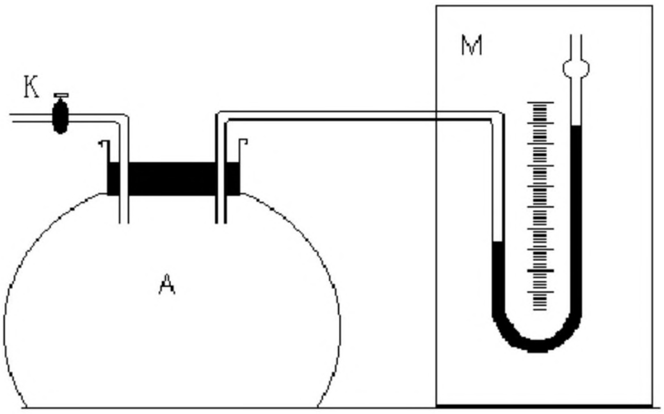
Student's name ____

Laboratory report M6

STUDY OF BASIC PRINCIPLES OF THERMODYNAMICS. DETERMINATION OF C_p/C_V FRACTION FOR AIR

Objective: to master the basic principles of molecular physics and thermodynamics. To determine C_p/C_V fraction for air experimentally.

EQUIPMENT



1. Hermetic container.
2. Manometer.
3. Pump.

COMPUTATION FORMULA

$\gamma = C_P / C_V = h_1/(h_1 - h_2)$.

	h_1, 10^{-2} m	h_2, 10^{-2} m	γ	$\Delta\gamma$	ε, %
1					▨
2					
3					
4					
5					
Mean value	▨	▨			

Student's name ____

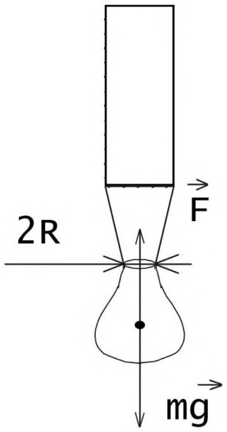
Laboratory report M7

DETERMINATION OF SURFACE TENSION BY COMPARING LIQUID DROPS

Objective: to master conception of surface tension in liquid. To determine surface tension of the liquid under investigation by comparing liquid drops.

EQUIPMENT

1. Burette.
2. Studied liquid.
3. Distilled water.
4. Measuring glass.



COMPUTATION FORMULA

$$\alpha_2 = \alpha_1 \frac{V_2 \rho_2}{V_1 \rho_1}$$

	α_1, 10^{-3} N/m	$\Delta\alpha_1$, 10^{-3} N/m	V_1, 10^{-6} m^3	ΔV_1, 10^{-6} m^3	ρ_1, kg/m^3	$\Delta\rho_1$, kg/m^3	V, 10^{-6} m^3	ΔV_2, 10^{-6} м^3	ρ_2, kg/m^3	$\Delta\rho_2$, kg/m^3	α_2, 10^{-3} N/m	$\Delta\alpha_2$, 10^{-3} N/m	ε, %
1 2 3	▨	▨			▨	▨			▨	▨	▨	▨	▨

Student's name ____

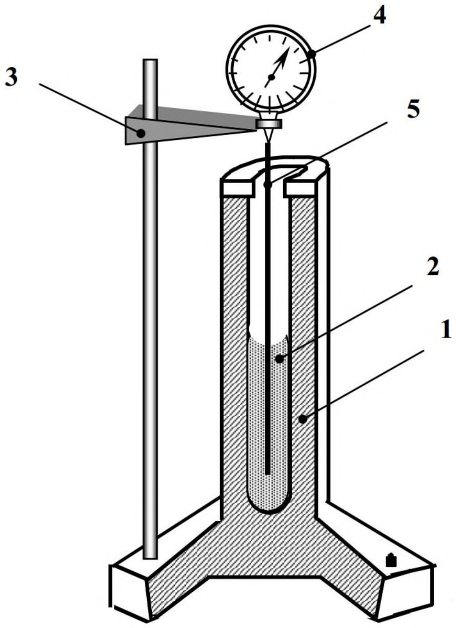
Laboratory report M8

DETERMINATION OF THERMAL EXPANSION COEFFICIENT FOR A SOLID

Objective: to determine experimentally the thermal expansion coefficients for different metals

EQUIPMENT

1. Heater.
2. Test-tube.
3. Micrometer indicator of expansion.
4. Metal rods.
5. Vernier caliper.
6. Thermometer.



COMPUTATION FORMULA

$$\alpha = \frac{\Delta l}{l_1 \Delta T} = \frac{\Delta l}{l_1 \Delta t}$$

	l_2-l_1, 10^{-3} m	$\Delta(l_2$-$l_1)$, 10^{-3} m	l_1, 10^{-3} m	Δl_1, 10^{-3} m	t_1, °C	Δt_1, °C	t_2, °C	Δt_2, °C	α, 10^{-6} K^{-1}	$\Delta\alpha$, 10^{-6} K^{-1}	ε, %
1											
2											
3											

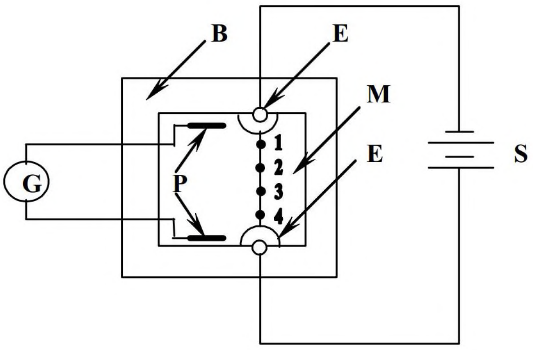
Student's name ____

Laboratory report E1

STUDY OF ELECTRIC FIELD BY PROBE METHOD

Objective: to work out a theoretical model of electrostatic field using equipotential contours and electric field lines of electric dipole.

EQUIPMENT



1) Galvanometer;
2) metallic probes;
3) two electrodes;
4) bench insulator for electrodes and paper sheet;
5) emf source;
6) metallic leads;
7) ruler, pencil, paper, water.

COMPUTATION FORMULAS

$$\Delta\varphi = n \cdot c \cdot R$$

$$E_l = -\frac{\Delta\varphi}{\Delta l}$$

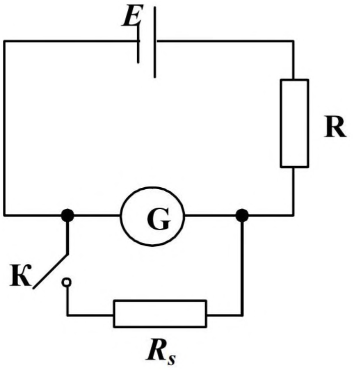
Distance between points, Δl	Galvanometer reading, n	Galvanometer's graduation mark, c	Resistance of the galvanometer, R	$\Delta\varphi$, V	E_l, V/m

Student's name ____

Laboratory report E2

DETERMINATION OF SCALE GRADUATION MARK AND INTERNAL RESISTANCE OF GALVANOMETER

Objective: determination of scale graduation mark and internal resistance of galvanometer by shunt method.



EQUIPMENT

1) Galvanometer of magneto-electric system;
2) shunt (0-900 Ω);
3) resistor bank (0,01 Ω – 10000 Ω);
4) current source of known emf (accumulator or electrical element);
5) switches.

COMPUTATION FORMULAS

$$R_g = \frac{R_s(n_1 R_1 - n_2 R_2)}{n_2(R_2 + R_s) - n_1 R_s}$$

$$C_a = \frac{E}{n_1(R_g + R_1)}$$

	Galvanometer scale deflection at shunt disconnected			**Resistances**			**Galvanometer scale deflection at shunt connected**		
	n_1	n'_1	$n_0 = \frac{n_1 + n'_1}{2}$	R_1	R_2	R_s	n_2	n'_2	$n = \frac{n_2 + n'_2}{2}$
1.									
2.									
3.									
Mean value									

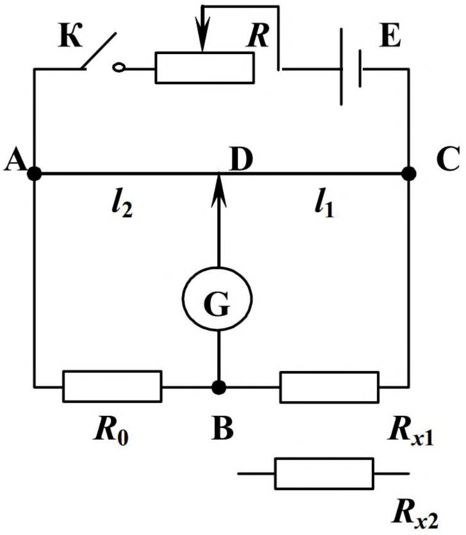
Student’s name ____

Laboratory report E3

DETERMINATION OF RESISTANCE WITH WHEATSTONE BRIDGE

Objective: to study direct current laws and master Wheatstone method of resistance determination.

EQUIPMENT



1) Current source of known emf;
2) galvanometer of magneto-electric system;
3) variable resistor;
4) studied resistors;
5) rheochord, rheostat;
6) switch and connecting wires.

COMPUTATION FORMULA

$$R_x = R_0 \frac{l_1}{l_2}$$

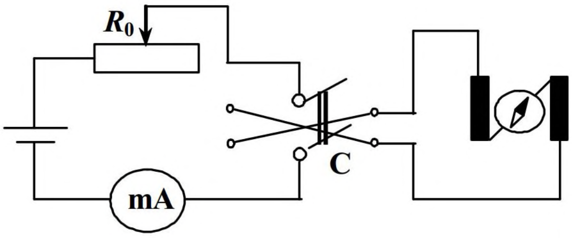
Resistance		**R_0, Ω**	**l_1, mm**	**l_2, mm**	**R_x, Ω**	**ΔR_x, Ω**	**$R_{mean.}$, Ω**	**$\Delta R_{mean.}$, Ω**	**ε_x, %**
R_{x1}	**1**								
	2								
	3								
R_{x2}	**1**								
	2								
	3								
In series R_{x1} and R_{x2}	**1**								
	2								
	3								
In parallel R_{x1} and R_{x2}	**1**								
	2								
	3								

Student's name ____

Laboratory report E4

DETERMINATION OF HORIZONTAL COMPONENT OF THE EARTH'S MAGNETIC FIELD USING HELMHOLTZ COIL

Objective: To determine the horizontal component of the Earth's magnetic field using Helmholtz coil.



1 EQUIPMENT

1) Power source;
2) Helmholtz's coil;
3) compass;
4) milliammeter;
5) rheostat.

COMPUTATION FORMULA

$$H_h = \frac{0.7156}{tg\alpha} \cdot \frac{I \cdot n}{R}$$

$$B_h = \frac{8.988 \cdot 10^{-7}}{tg\alpha} \cdot \frac{I \cdot n}{R}$$

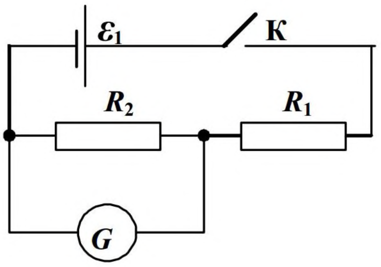
	α	***I*,** **A**	***n***	***R*,** **m**	***B*** **T,**	***H*,** **A/m**
1						
2						
3						
Mean value						

Student's name ____

Laboratory report E5

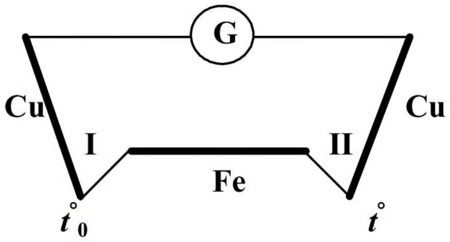
THERMOCOUPLE CALIBRATION

Objective: to learn elementary theory of Seebeck effect and to calibrate a thermocouple.



EQUIPMENT

1) Thermocouple;
2) Galvanometer;
3) Thermometer;
4) Thermostat;
5) Voltmeter;
6) Resistors, connecting wires and switch;
7) Battery of known emf;
8) Electric heater.



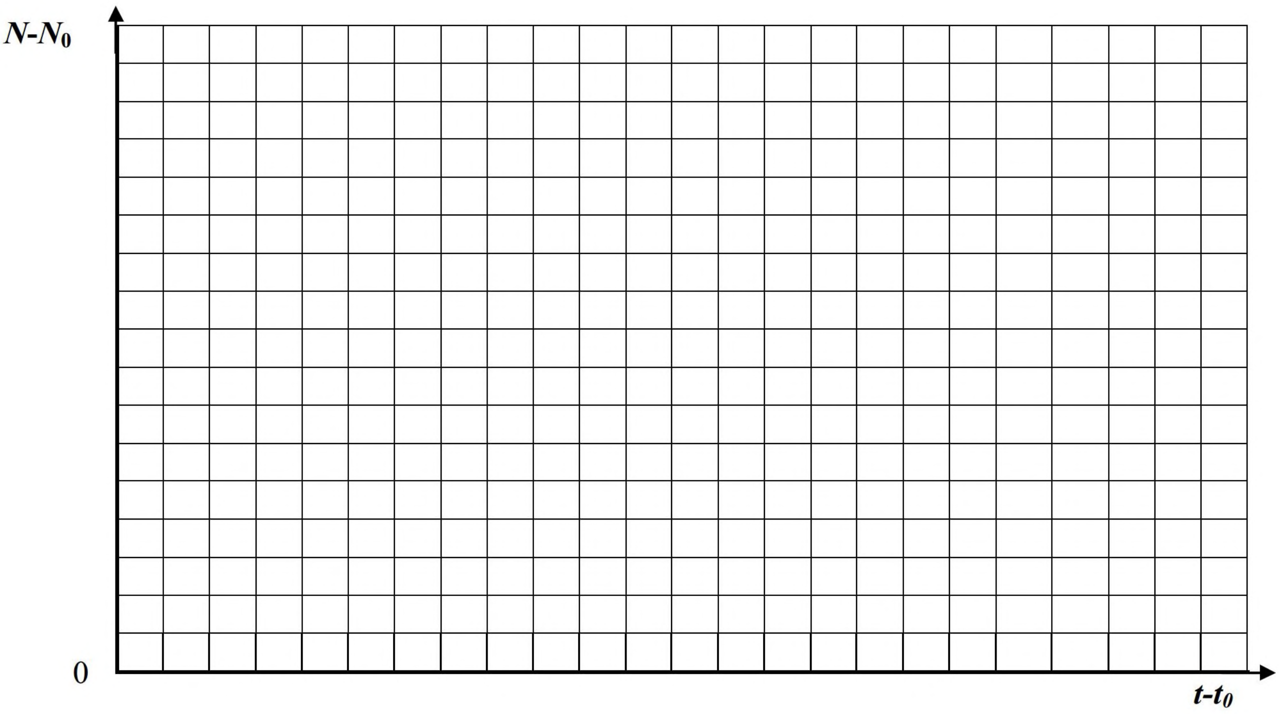
COMPUTATION FORMULAS

$$C = \frac{\varepsilon_1 R_2}{(R_2 + R_1)N}$$

$$n = \frac{N}{t^\circ - t_0^\circ}$$

$$\alpha = Cn$$

t_1, °C									
N_1									

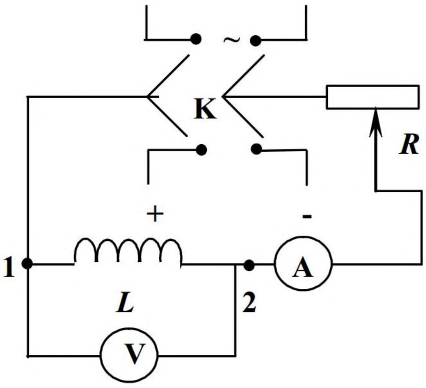


Student's name ____

Laboratory report E6

EXAMINATION OF OHM'S LAW FOR ALTERNATING CURRENT

Objective: to examine Ohm's law experimentally; to master methods of AC measurements.



EQUIPMENT

1) Inductor (coil);
2) capacitor;
3) AC ammeter and voltmeter;
4) two switches;
5) rheostat;
6) AC and DC sources.

COMPUTATION FORMULAS

$$R_0 = \frac{U_0}{I_0}$$

$$R_1 = \frac{U_{rms}}{I_{rms}} \qquad L = \frac{\sqrt{R_1^2 - R_0^2}}{\omega}$$

$$R_2 = \frac{U_{rms}}{I_{rms}} \qquad C = \frac{1}{\omega R_2}$$

$$Z_1 = \frac{U_{rms}}{I_{rms}}$$

$$\frac{\Delta Z_1}{Z_1} = \frac{\Delta U_{rms}}{U_{rms}} + \frac{\Delta I_{rms}}{I_{rms}}$$

$$Z_2 = \sqrt{R_0^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}$$

U_0	I_0	R_0	U^L_{rms}	I^L_{rms}	R_1	L	U^C_{rms}	I^C_{rms}	R_2	C

U_{rms}	I_{rms}	Z_1	Voltmeter's grade of accuracy	Ammeter's grade of accuracy	ΔZ_1	Z_2

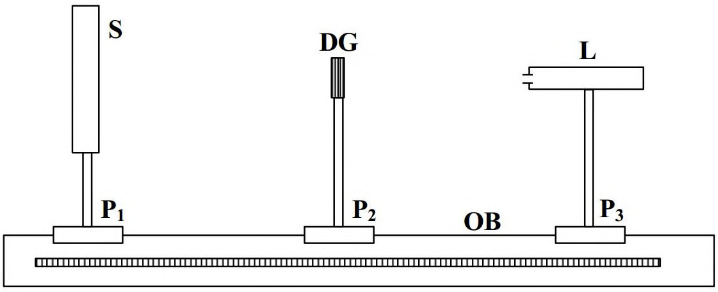
Student's name ____

Laboratory report O1

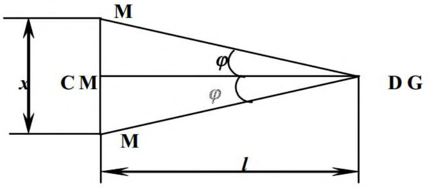
DETERMINATION OF WAVELENGTH BY DIFFRACTION GRATING

Objective: to investigate diffraction phenomena and determine the light wavelength with a diffraction grating.

EQUIPMENT:



1) optical bench with millimeter scale;
2) laser;
3) diffraction grating;
4) screen with millimeter scale.



COMPUTATION FORMULA

$$\lambda = \frac{xd}{2kl}$$

	d, 10^{-3} m	k -	l, 10^{-3}, m	x, 10^{-3} м	λ, 10^{-9} m	$\Delta\lambda$, 10^{-9}, m	ε, %
1							
2							
3							
Mean value							

Student’s name ____

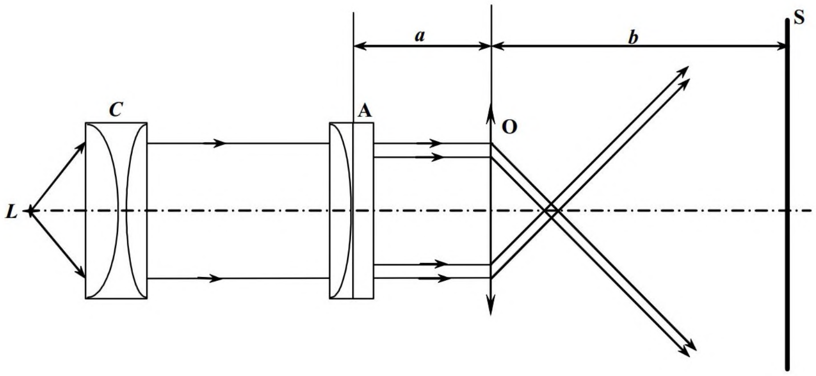
Laboratory report O2

DETERMINATION OF LIGHT WAVELENGTH USING NEWTON’S RINGS

Objective: determination of light wavelength from interference phenomenon.

EQUIPMENT:

1) photographic enlarger;
2) object-glass;
3) Newton’s apparatus;
4) screen;
5) sheet of white paper;
6) pencil.



COMPUTATION FORMULAS

$$r' = \frac{a}{b} r_n$$

$$\lambda = \frac{(r_i - r_k)(r_i + r_k)}{(i-k)R}$$

N	1	2	3	4	5
r_n, mm					
r'_n, mm					

i	k	r_1, mm	r_k, mm	λ, nm	$\Delta\lambda$, nm	ε, %
Mean values						

Student’s name ____

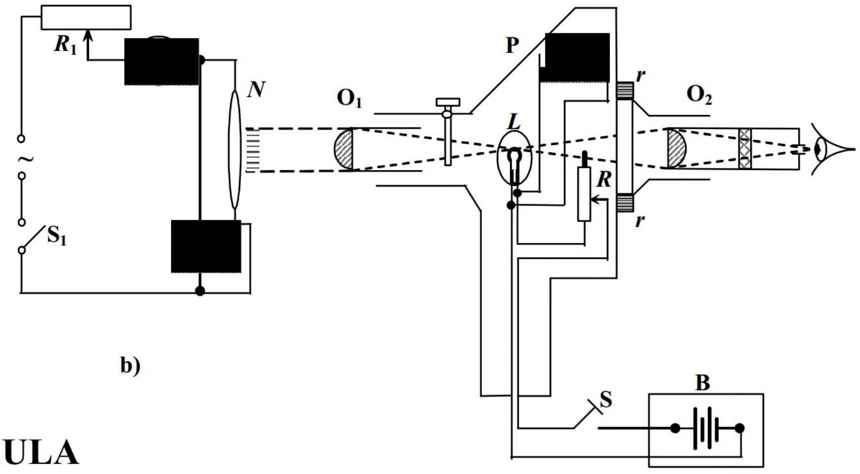
Laboratory report O3

DETERMINATION OF STEFAN-BOLTZMAN CONSTANT

Objective: Study of thermal radiation. Determination of Stefan-Boltzman’s constant with use of pyrometer.

EQUIPMENT:

1) pyrometer;
2) voltmeter;
3) step-down transformer;
4) voltage regulator;
5) bulb lamp.



COMPUTATION FORMULA

$$\sigma = \frac{IV}{A\left(T^4 - T_0^4\right)}$$

	V, V	I, A	T_0, K	T, K	σ, W/m$^2\cdot$K^4	$\Delta\sigma$, W/m$^2\cdot$K^4	ε, %
1							▨
2							▨
3							▨
Mean values	▨	▨	▨	▨			

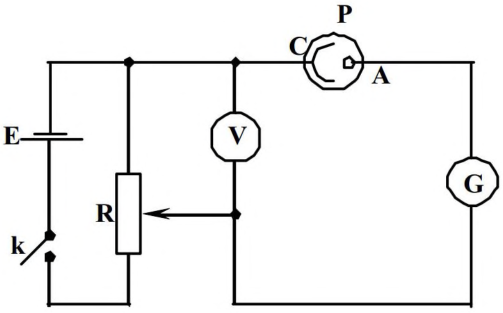
Student's name ____

Laboratory report O4

STUDY OF VOLTAGE-CURRENT CHARACTERISTIC AND SATURATION CURRENT OF EMISSION PHOTOTUBE

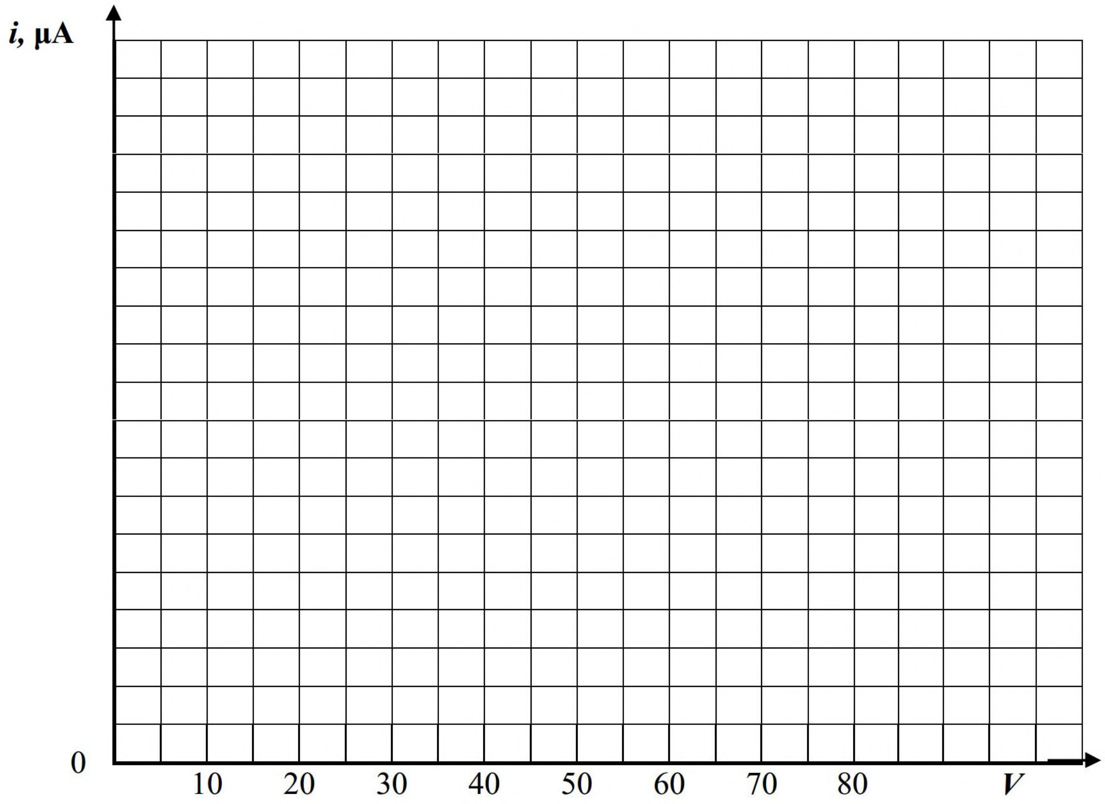
Objective: to master laws of photoemission, to obtain voltage-current characteristics and to determine saturation current for phototube.

EQUIPMENT



1) lighting chamber with scale ruler;
2) vacuum phototube;
3) light bulb of known luminous intensity;
4) electric power supply;
5) voltmeter;
6) ammeter.

	l, cm	*V*, V	0	20	30	40	50	60	70	80	90	100
1		***i*, μA**										
2		***i*, μA**										
3		***i*, μA**										

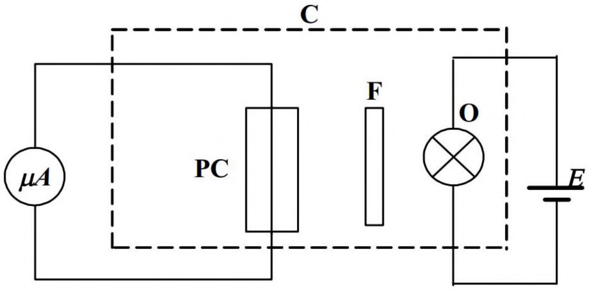


Student's name ____

Laboratory report O5

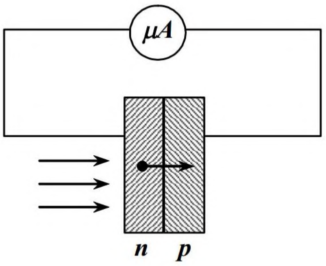
DETERMINATION OF SPECTRAL SENSITIVITY OF SEMICONDUCTING PHOTOCELL

Objective: to study the photoconductivity phenomenon and to estimate the spectral sensitivity of semiconducting photocell.



EQUIPMENT:

1) lightproof chamber with the studied photocell and a lamp;
2) light-filter set;
3) energy source;
4) microammeter.



COMPUTATION FORMULA

$$i_\lambda = K_\lambda \cdot i$$

$$\gamma_\lambda = \frac{i_\lambda \cdot l^2}{JS}$$

light filter	λ, nm	K_λ	i, μA	i_λ,	γ_λ, μA /lm
red		1.12			
orange		1.06			
yellow		1.03			
green		0.96			
blue		0.92			
violet		0.89			

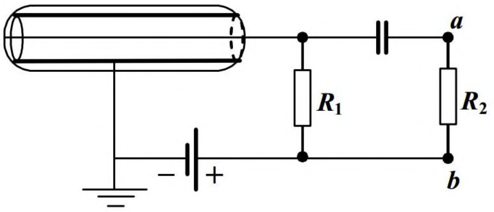
Student’s name ____

Laboratory report O6

STUDY OF GAMMA ABSORPTION OF A MATTER USING THE GEIGER COUNTER

Objective: to learn radioactive decay law, to determine gamma absorption of lead.

EQUIPMENT



1) Geiger counter of gamma-particles;
2) Lead plates;
3) Micrometer.

COMPUTATION FORMULA

$$\mu = \frac{1}{x} \cdot \ln \frac{I_0}{I}$$

	I_{bg}	I_0	I	x 10^{-3} m	μ m^{-1}
1					▨
2					▨
3					▨
mean value					