MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE
Kyiv National University of Construction and Architecture

PHYSICS

Excel–Based Laboratory Course Manual

Recommended by the Scientifically Methodical Council
Kyiv National University of Construction and Architecture
as a Course Manual for students of all specialities of KNUCA

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Compileres: O.V. Panova, PhD in Technical Science, Associate Professor
I.O. Aznaurian, Associate Professor
H.Yu.Krasnyansky, PhD in Technical Science, Associate Professor
V.I. Klapchenko, PhD in Technical Science, Associate Professor
V.A. Hlyva, Doctor of Technical Science, Professor
I.O. Kuznetsova, Assistant
Y.I. Biruk, Assistant

Reviewer: ***Alexander Zaporozhets****, Doctor of Technical Sciences, Professor, Vice-Rector for International Cooperation and Education NAU;*
Vitalij Ploskij*, Doctor of Technical Sciences, Professor, Head of the Department of Architectural Structures, Vice-Rector for Scientific Activities KNUCA;*
Oleksandr Podoltsev*, Doctor of Technical Sciences, Senior Scientist, Institute of Electrodynamics of the National Academy of Sciences of Ukraine*

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Contains training materials to perform basic level laboratory work using the Excel package.

The material is presented in English for use by students who are fluent in it or want to improve their knowledge of English, and foreign students.

Intended for students of all specialties KNUCA.

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CONTENT

INTRODUCTION

Laboratory workshop is an important part of learning process, the most effective form of improving cognitive student’s abilities. It provides opportunity to reproduce and observe physical phenomena by yourself. With experiments, you would check physical laws and their consequences. In addition, you would find out principle of action and structure of measuring devices and get to know the most important methods of physical experiment. Laboratory workshop forms independent research work skills in students and learns how technically-correctly physic quantities measure. Moreover, workshop illustrates, deepens, broadens and substantiates theoretical course of physics. Consequently, one of the most important stage on education, done: we combine theory and practice.

While students perform laboratory work, they spent a lot of time in processing the results of measuring and paperwork (filling tables and building graphics). As a result, there is not enough time to analyze received results. This paperwork on calculations and results can be minimized by using MS Excel.

While holding the laboratory of physic, you often have to calculate the same physic measures for several experiments. This problem is solved, if all values are given in the form of spreadsheet and this gives the opportunity not only reflect, but and process them. For the description of the connection among different cell tables, formulas are used. Calculation according to given formulas is done automatically. The change in one cell table provides to recalculation values in all cell tables connected with this one by formula interrelation and then updates the whole table according to changed data. The using of spreadsheet makes the work with data much easier and allows getting results without manual calculations or special programming.

It is often necessary to build graphics of value dependencies based on tables, during the laboratory work. With a help of diagram Master and various Excel Chart Library graphs and charts of diverse types can be made. A result of research that is presented in graphics, assist in better analyzing of phenomena and provides clearness. Furthermore, the usage of spreadsheet helps not only to save time in lessons, but provides interpersonal contact with computer science.

Realization of each laboratory work involves separate **stages**:

1. Self-dependent home preparation of laboratory work.
2. Obtaining permission for work realization.
3. Work realization and fixing results of measuring.
4. Report figuration.
5. Laboratory defense.

Let’s consider each stage in details.

1. **Self-dependent preparation at home.**

A student who knows the number of his/her brigade determines the number and name of the laboratory work to be performed in this lesson by the graph. To prepare for the laboratory work you have to use recommended methodical instructions in home or reading room. By the time of preparation, you may consult with lecturer. Because of it, you must have:

- the summary of methodical instructions for present laboratory work in laboratory copybook;
- the possession of theoretic materials in an enough amount of the topic of work (for these you may use instructions to laboratory work, control questions to laboratory work or your textbook);
- the skill of clear formulating topic, purpose and task for present laboratory work;
- the knowledge of methodic of completion laboratory work and necessary equipment which in use on present work.

2. How to get permission for laboratory work realization?

To get permission for performing present laboratory work, you are ought to:

- ✓ have abbreviated (or full) notation of methodic materials in student’s laboratory copybook. Notations are necessary as in work completing, as in report figuration and defensing of laboratory work. Theoretical information about recommended literature may be given in abbreviated form;
- ✓ know purpose of work and specific task, which student have to do;
- ✓ know in which order, how and what to measure;
- ✓ know which materials, instruments and devices are necessary in work;
- ✓ have layout of tables for entering data of measurements, calculations and building graphics in Excel.

When permission received the lecturer warns (sometimes caution) what is forbidden to do or allowed only with supervision of lecturer or laboratory assistant.

3. Work realization and fixing results of measuring.

Student implements the work under supervision of lecturer. Electrical circuits are included in the circle only after check of lecturer or laboratory assistant. The performance of the laboratory work is recorded in the laboratory journal when the measurement results are recorded in the student’s laboratory notebooks.

4. **How to figurate report correctly?**

Calculating results of measurements, building graphics and report figuration done on laboratory lessons under control of lecturer or independently outside of classes. The report consists of sheets of A-4 format with title and pages with results of measurements. The report is submitted in printed form to lecturer.

5. **How to defense laboratory work?**

General principles about laboratory work defense are:

- students are admitted to work defensing if they did work and acceptance of correctly figurate report;
- work defense is confirmation students` understanding of theoretic principles, physics appellations, conceptions surrounded around control question (they are given at the end of every work), in conversation with lecturer;
- additional questions may be asked for putting a mark "good" or "excellent" and intended for better understanding nature of physics phenomena by student;
- result of asking is recorded into laboratory journal with appreciate mark.

Kyiv National University of Construction and Architecture

Department of Physics

REPORT

Laboratory

____

____

(title of lab.)

Student_____________________________

(surname, initials)

____

(group)

____

(faculty)

Date of implementation: _____________

Date of submission: _________________

___________________________	___________________________
(job acceptance note)	(surname of lecturer and signature)

Laboratory 14

Determination of Absolute and Relative Air Humidity

Objective:

- Study the features of gases and steams of air liquids.
- Determine the absolute and relative humidity of the air.

Equipment List

- Psychrometer
- Barometer
- Glass with water
- Dropper

Theory

Atmospheric air is known to be a mixture of gases containing 78% nitrogen, 21% oxygen and a small amount of CO_2, water steam and other gases. The content of water steam in the atmosphere is characterized by humidity. In practice, it is important to be able to determine the amount of water steam in the air at a certain temperature. Measuring humidity and maintaining a certain level of moisture are required in many businesses (industrial, weaving, confectionery), in various storage facilities (libraries, museums, archives), hospitals and premises. Meteorologists determine the changes in the weather by changing the humidity. In general, humidity significantly affects the development of flora and fauna on Earth, human life and determines the comfort of the premises.

The total atmospheric pressure consists of the partial pressures of the individual components. Water steam pressure is partial, one of the components of full atmospheric pressure. Usually the partial pressure of water steam in the atmosphere varies with in $(0.005 \div 0.05) \cdot 10^5$ Pa.

Quantitatively humidity is estimated by absolute and relative humidity. Absolute humidity is a physical value equal to the mass of water steam contained in 1 m^3 of air at a given temperature. In other words, absolute humidity is equal to the density of water steam at a given temperature. The mass of 1 m^3 of dry air under normal conditions is 1293 g. Based on the Clapeyron equation, the mass of 1 m^3 of air at temperature $t^{0}\mathrm{C}$ and pressure p, mm Hg. Art. will be equal to:

$$m = \frac{1293}{1+\alpha t^{o}} \cdot \frac{p}{760}\,\mathrm{g},$$

where $\alpha = \frac{1}{273} deg^{-1}$ – coefficient of linear expansion of air.

The density of water steam relative to the density of air at the same pressure and temperature is 0.622. The Clapeyron equation (valid only for water steams far from saturation) gives for the mass *m* of 1 m^3 of water steam the equation:

$$AH = m = \frac{1293 \cdot 0.622}{760} \cdot \frac{p}{1+\alpha t^{o}} = 1.06 \frac{p}{1+\alpha t^{o}}. \qquad \text{(Eq. 14.1)}$$

This expression allows determining the absolute humidity, if the known partial pressure *p* of water steams at a given temperature. It can be seen from equation (14.1) that, at low temperature *t* values, the absolute humidity *b* is actually proportional to the water steam pressure *p*. There fore, the absolute humidity expressed by partial pressure, sometimes called the *elasticity of water steam* and measured in units of pressure – mm Hg. Art.

However, absolute humidity does not always make it possible to estimate the degree of air saturation with water steam. Therefore, in practice, they use a relative characteristic – relative humidity, which is defined as the relative saturation of air with water steam.

Relative humidity (*RH)* is the ratio of the partial pressure of water steam at a given temperature t to the pressure of a saturated steam at the same temperature p_S:

$$RH = \frac{p\left(t\ {}^{o}\mathrm{C}\right)}{p_S\left(t\ {}^{o}\mathrm{C}\right)}100\%. \qquad \text{(Eq. 14.2)}$$

Therefore, in order to find the relative humidity of the air, one must know the partial pressure of steam at a given temperature and the pressure of saturated steam at the same temperature. The partial pressure of water steam at a given temperature can be found by knowing the dew point. The *dew point* is the temperature at which water steam in the air becomes saturated. When water steam is cooled below the dew point, it begins to condense on solid surfaces (dew acts). The relative humidity of the air can also be determined by the density of the water steam.

The most common humidity meter is a psychrometer. The most common instrument for measuring humidity is a *psychrometer,* which consists of two identical thermometers, one of which is wrapped with a damp light cloth (a "humid" thermometer). If the water steam in the air is unsaturated (RH<100%), the water from the cloth will evaporate. At the same time, the readings of the "humid" thermometer are lower than the dry ones due to evaporation. The less steam in the air, the more intense the evaporation and lower readings of the "humid" thermometer. The difference between the temperature of the "dry" thermometer t_d and the temperature of the "humid" thermometer t_h is proportional to the humidity of the air: the drier the air, the greater the difference; if the air is saturated with steam, then $t_d = t_h$, since the partial pressure of water steam in the air is equal to the saturation pressure of water steam at temperature t_d. The difference between the readings of these thermometers and the psychometric table (see Table 14.3) find the values of humidity.

Besides the psychrometer, *hygrometers* are also used to measure humidity. For example, the principle of action of a hair hygrometer (from the Greek hydro’s – humid) is based on the fact that in humid air the length of stretched human hair grows, and in dry – shortens. Measuring the elongation of the hair draw conclusions about the value of humidity.

This laboratory work uses an aspiration psychrometer (Fig. 14.1), the principle of which is that two identical thermometers are blown by the same air flows. The reservoir of one of the thermometers is wrapped in water-soaked bath. Due to the evaporation of water, the thermometers are different. A "humid" thermometer has a lower temperature compared to a "dry" thermometer.

Evaporation of water by a free surface per unit of time is proportional to the difference in water and air temperatures (Newton law):

$$Q_1 = a \cdot \Delta t \cdot S_1, \qquad \text{(Eq. 14.3)}$$

where Q – the heat of evaporation; a – the coefficient of proportionality; Δt – the difference between «dry» and «humid» thermometers; S_1 – the value of the evaporation surface.

Evaporation of liquid per unit time is determined by the formula:

$$m = \frac{c \cdot S^2 \left(p_S - p \right)}{P}, \qquad \text{(Eq. 14.4)}$$

where m – the mass of evaporated water;
c – coefficient of proportionality;
S_2 – the area of the evaporating surface;
p_S – the elasticity of saturated water steam at a given temperature;
p – the elasticity of water steam in the air;
P – the atmospheric pressure of the air under these conditions.

The amount of heat Q_2 required for evaporation of water by mass m is equal to:

$$Q = m \cdot r = \frac{c \cdot S^2 \left(p_S - p \right)}{P} \cdot r, \qquad \text{(Eq. 14.5)}$$

where r – the specific heat of evaporation.

For $Q_1 = Q_2$ from (Eq. 14.3, Eq. 14.5):

$$\alpha \cdot \Delta t \cdot S_1 = \frac{c \cdot S^2 \left(p_S - p \right)}{P} \cdot r, \qquad \text{(Eq. 14.6)}$$

and because $S_1 = S_2$, so:

$$p = p_S - A \cdot \Delta t \cdot P, \qquad \text{(Eq. 14.7)}$$

where A – a constant for the device value (constant psychrometer), which is determined by the speed of air flow and is experimentally:

$$A = \frac{a}{c \cdot r} = \text{const.}$$

Ultimately, the formula for calculating the absolute humidity is:

$$AH = p = p_S - 0{,}002 \cdot \left(t_d - t_h \right) \cdot P, \qquad \text{(Eq. 14.8)}$$

where p_S – the saturated steam pressure at the humid thermometer temperature t_h;

p_d is the temperature of the dry thermometer;

P – atmospheric pressure of air determined in mm Hg. Art.

The value of p_S is taken from the table "Dependence of the pressure of saturated water steam on temperature" (Table 14.4). The atmospheric pressure is determined using a barometer.

The structure of a standard aspiration thermometer is shown in Figure 14.1. It consists of two identical thermometers *T*, the canister of one of the thermometers is covered with a batiste *B*. The aspirator has a spring fan, which is started with a *K* key.

Air velocity is close to 2.5 m/s. To prevent the device from heating outside, its metal parts have a mirror coating. Batiste is moistened with water using a rubber pear with a pipette. The pear is filled with distilled water. A small squeeze of the pear through the pipette is wetted by the batiste. The water on the second thermometer should be avoided. The K key is turned on the fan for 5-6 turns and watches the thermometers.

Nowadays, electronic psychrometers are used in practice to determine the relative humidity (Fig. 14.2).

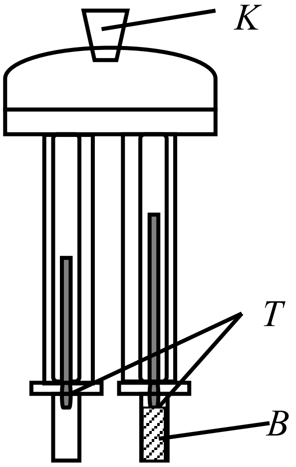

Fig.14.1

Fig.14.2

Pre-Laboratory Assignment

To perform the work, you need to study such a theoretical material: real gases, saturated and unsaturated steams; features of distribution of moisture in air; humid air characteristics.

Experimental Procedure

Method I

1. With the help of a pear, wet the batiste, which is wound on the reservoir of one of the psychrometer thermometers (B).
2. Start the mechanical device of the fan (K) at 5-6 full revolutions.
3. After 4-5 minutes, remove the "dry" t_d and "wet" t_h thermometers.
4. Write the results of measurements in Table 14.1.

Method II

1. Using a barometer to determine the atmospheric pressure P.
2. For the Table 14.2 find the value of saturated steam pressure p_s at a temperature corresponding to the readings of the "humid" thermometer t_h.
3. Write the results of measurements in Table 14.1.

Calculations

Method I

1. Find the temperature $\Delta t = t_d - t_h$ difference and determine the relative humidity RH using a psychometrics table (Table 14.3).
2. Write the results of the calculations in Table 14.1.

Method II

1. Using formula (14.8) to calculate the absolute humidity AH in Excel.
2. For the Table 14.2 find the value of the saturated steam pressure of the p_s at a temperature that corresponds to the readings of the "dry" thermometer.
3. Using formula (14.2) to calculate the relative humidity RH in Excel.
4. Perform all calculations in Excel and write them in Table 14.2.
5. Make a report in the form of Excel table.

Laboratory Report

Data and Calculations Table 14.1

t_d, °C	t_h, °C	Δt, °C	*RH*, %

Data and Calculations Table 14.2

$P_S(t_h)$, mm Hg. Art.	$P_S(t_h)$, Pa	*P*, mm Hg. Art.	P, Pa	$P_S(t_d)$, mm Hg. Art.	$P_S(t_d)$, Pa	*AH*, mm Hg. Art.	*AH*, Pa	*RH*, %

Table 14.3

Dependence of saturated water vapor pressure on temperature

t, °C	P_s, mm Hg. Art.	***t***, °C	P_s, mm Hg. Art.	***t***, °C	P_s, mm Hg. Art.
-30	0.28	-3	3.57	24	22.38
-29	0.31	-2	3.88	25	23.76
-28	0.35	-1	4.22	26	25.21
-27	0.38	0	4.58	27	26.74
-26	0.43	1	4.93	28	28.35
-25	0.47	2	5.29	29	30.04
-24	0.52	3	5.69	30	31.82
-23	0.58	4	6.10	31	33.70
-22	0.64	5	6.54	32	35.66
-21	0.70	6	7.01	33	37.73
-20	0.77	7	7.51	34	39.90
-19	0.85	8	8.05	35	42.18
-18	0.94	9	8.61	36	44.56
-17	1.03	10	9.21	37	47.07
-16	1.13	11	9.84	38	49.69
-15	1.24	12	10.52	39	52.44
-14	1.36	13	11.23	40	55.32
-13	1.49	14	11.99	45	71.88
-12	1.63	15	12.79	50	92.50
-11	1.78	16	13.63	55	118.00
-10	1.95	17	14.53	60	149.40
-9	2.13	18	15.48	65	187.50
-8	2.32	19	16.48	70	233.70
-7	2.53	20	17.54	75	289.10
-6	2.76	21	18.65	80	355.10
-5	3.01	22	19.83	90	525.80
-4	3.28	23	21.07	100	760.00

Table 14.4

Psychometric table

Dry thermometer readings, °C	Difference between dry and humid thermometers, °C											
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
	Relative humidity, %											
0	100	81	63	45	28	11						
1	100	83	65	48	32	16						
2	100	84	68	51	35	20						
3	100	84	69	54	39	24	10					
4	100	85	70	56	42	28	14					
5	100	86	72	58	45	32	19	6				
6	100	86	73	60	47	35	23	10				
7	100	87	74	61	49	37	26	14				
8	100	87	75	63	51	40	29	18	7			
9	100	88	76	64	53	42	31	21	11			
10	100	88	76	65	54	44	34	24	14	5		
11	100	88	77	66	56	46	36	26	17	8		
12	100	89	78	68	57	48	38	29	20	11		
13	100	89	79	69	59	49	40	31	23	14	6	
14	100	89	79	70	60	51	42	34	25	17	9	
15	100	90	80	71	61	52	44	36	27	20	12	5
16	100	90	81	71	62	54	46	37	3O	22	15	8
17	100	90	81	72	64	55	47	39	32	24	17	10
18	100	91	82	73	65	56	49	41	34	27	20	13
19	100	91	82	74	65	58	50	43	35	29	22	15
20	100	91	83	74	66	59	51	44	37	3O	24	18
21	100	91	83	75	67	60	52	46	39	32	26	20
22	100	92	83	76	68	61	54	47	40	34	28	22
23	100	92	84	76	69	61	55	48	42	36	3O	24
24	100	92	84	77	69	62	56	49	43	37	31	26
25	100	92	84	77	70	63	57	50	44	38	33	27
26	100	92	85	78	71	64	58	51	46	40	34	29
27	100	92	85	78	71	65	59	52	47	41	36	30
28	100	93	85	78	72	65	59	53	48	42	37	32
29	100	93	86	79	72	66	60	54	49	43	38	33
30	100	93	86	79	73	67	61	55	50	44	39	34

Questions

1. What is a saturated and unsaturated steam?
2. What is absolute humidity?
3. What is relative humidity?
4. What are the humidity measurement methods?
5. What energy does the liquid evaporate?
6. What is the dew point?
7. How is the psychrometer, hygrometer built?
8. What is the basis of the psychrometric method for measuring humidity?
9. For what purpose should humidity be controlled?
10. Give the approximate composition of the atmosphere.

Laboratory 2.2

Determination of the Coefficient of Thermal Conductivity of Solids by the Method of Regular Mode

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Objective:

- Explore the heat transfer phenomena.
- Measure ebony's thermal conductivity.

Equipment List

- Thermometer
- Cylinder
- Heater
- Vessel with water
- Stopwatch
- Ccalipers or ruler

Theory

In thermodynamical systems there are irreversible processes, which are called heat transfer phenomena. They cause special energy (thermal conductivity), mass (diffusion) i amount of movement (internal friction or viscosity) transfer. A distinctive feature of these processes is the fact that the energy, mass and amount of movement transfer always occurs in the direction opposite to the gradient of their special distribution, which means the system approaches the thermodynamic equilibrium.

In order to assess thermal conductivity coefficient, we can use the process of heat transfer in solids, because laws of such a process always involve the heat transfer coefficient.

Thermal conductivity can be inferred from the main equation in this domain – the Fourier's law:

$$\Delta Q = -\lambda \frac{\partial T}{\partial x} \Delta S \Delta\tau,$$

where ΔQ – amount of heat which is conducted along x axis through a unit of area ΔS during time $\Delta\tau$; $\partial T/\partial x$ – gradient of temperature.

From the Fourier equation we can infer:

$$\lambda = \frac{\Delta Q}{\partial T/\partial x \cdot \Delta S \cdot \Delta\tau}.$$

Therefore, the *coefficient of thermal conductivity* λ is numerically equal to the amount of heat transferred through a unit of cross-sectional area of the sample per unit time by a temperature gradient equal to one.

In practice it is hard to measure some of the values in the Fourier equation, so it's better to consider processes where we can measure all the necessary quantities precisely and easily and then calculate λ. One of such processes is a *regular mode of heating*.

Let the sample be heated to some temperature T into a medium that conducts heat well (for example water). The temperature of this medium is kept constant and equals T_0. Because of the thermal conductivity the temperature difference between the sample and the medium $T - T_0 = \Delta T$ decreases and at the moment of equilibrium equals zero. The law of this decrease, a function $\Delta T = f(\tau)$ depends on the size and shape of the sample, its thermophysical properties and whether the sample was heated up evenly or not before the experiment. During the first stage of heat transfer this law is considerably complex.

Gradually the so-called *regular mode of heating* (or cooling) begins where the temperature difference between any point of sample and medium is decribed by the law:

$$\Delta T(x,\tau) = A(x)e^{-a\tau}. \qquad \text{(Eq. 2.2.1)}$$

Quantity a in formula (2.2.1) is called the *rate of heating* (or cooling) and it depends on the substance properties:

$$a = \frac{\lambda}{kc\rho}, \qquad \text{(Eq. 2.2.2)}$$

where λ – coefficient of thermal conductivity; k – the shape coefficient of the sample; c – ebony's heat capacity; ρ – ebony's density.

The shape coefficient depends on substance shape and size. For a cylinder:

$$k = \frac{1}{\frac{5.78}{R^2} + \frac{9.87}{h^2}}, \qquad \text{(Eq. 2.2.3)}$$

where R – cylinder's radius; h –cylinder's height.

So, assessment of thermal conductivity coefitient λ of a cylindrical sample with known density ρ and specific heat capacity c is reduced to measuring the rate of heating a. For this we measure the temperature difference between the sample and the medium in different points in time.

According to the equation (2.2.1):

$$\ln\Delta T = \ln A - a\tau. \qquad \text{(Eq. 2.2.4)}$$

The function $\ln\Delta T = f(\tau)$ after the regular mode begins is depicted graphically as a straight line with a slope a.

Once we have concluded about the heating rate, we can estimate:

$$\lambda = a \cdot k \cdot c \cdot \rho. \qquad \text{(Eq. 2.2.5)}$$

We should choose boiling water as the medium because firstly in this case there is enough heat transfer between the surface of the substance and the water – a result of convection and secondly the boiling water's temperature is known and it doesn't change when the substance is heated up. The temperature is measured either with a common thermometer or a differential thermopair and a potentiometer and a recorder.

Pre-Laboratory Assignment

To perform the work, you need to study such a theoretical material: heat transfer; thermal conductivity.

Experimental Procedure

1. Turn the heater on and heat up the water till it boils. Keep the water temperature constant during the whole experiment 100 ^{o}C.
2. Put the cylinder into the water.
3. Recorder the temperature by thermometer every 60 s.
4. Write the results of measurements in Excel Table 2.2.1.

Calculations

1. Calculate the temperature difference between boiling water and sample temperature: $\Delta T = 100\,^{o}\mathrm{C} - t\,^{o}\mathrm{C}$ and ccalculate the logarithm ΔT in Excel.
2. Build a graph $\ln \Delta T = f(\tau)$ in Excel (see Fig. 2.2.1).
3. Select a straight section on the graph (regular interval), build a trend line on this section, and show the equation of this line.
4. From equation straight line determine *rate of heating a*.
5. Measure the diameter D and height h of the cylinder.
6. Calculate the radius R and calculate the coefficient of the form k by formula (2.2.3).
7. Record in table 2.2.1 the specific heat c and the density of ebonite ρ.
8. Apply formula (2.2.5) and calculate the coefficient of thermal conductivity of ebonite λ in Excel.
9. Make a report in the form of Excel table and graphs.

Laboratory Report

Data and Calculations Table 2.2.1

τ,s	t°C	ΔT, K	lnΔT	a, 1/s	D, m	R, m	h, m	k, m^2	c, J/(kg·K)	ρ, kg/m^3	λ, W/(m·K)

Graph

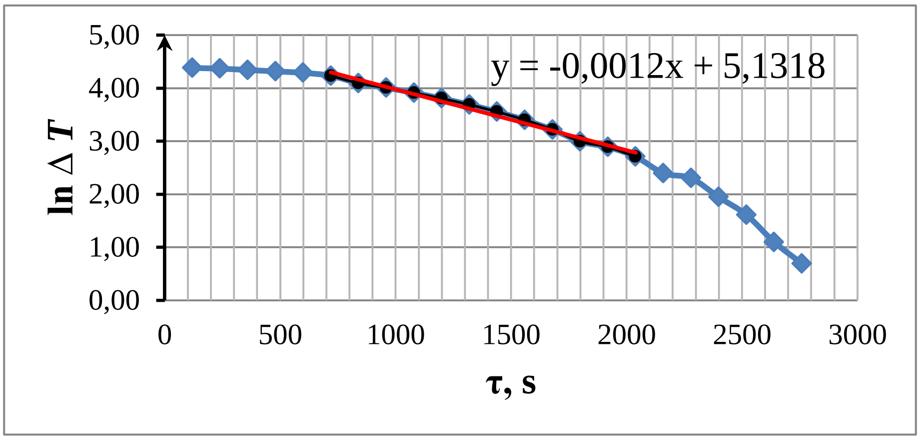

Fig. 2.2.1

Questions

1. What heat transfer phenomena do you know?
2. Give a defenition for heat transfer.
3. Write down the Fourier’s law for heat transfer.
4. What is the thermal conductivity coeficient? Explain its physical meaning.
5. On what depends thermal conductivity of solids?
6. What is the temperature gradient?
7. Explain the physical sense of the negative sigh in the Fourier’s law.
8. What is the regular mode of heating? Write down how the temperature depends on time during the regular mode heating.
9. Explain the practical importance of the thermal conductivity of construction materials.

Laboratory 4.1

Determination of Parameters of Fading of Oscillations of a Physical Pendulum

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Objective:

- Study basic laws of fading oscillations.
- Determine coefficient of fading and logarithmic decrement of physical pendulum oscillations fade.

Equipment List

- Physical pendulum
- Scale
- Stopwatch
- Calipers

Theory

Oscillation is a regular or almost regular process in which any magnitude takes same values at equal or almost equal time intervals.

Physical pendulum is a solid object with ability to perform oscillations around stationary horizontal axis, which does not pass through mass center of body under the action of gravity (Fig. 4.1.1).

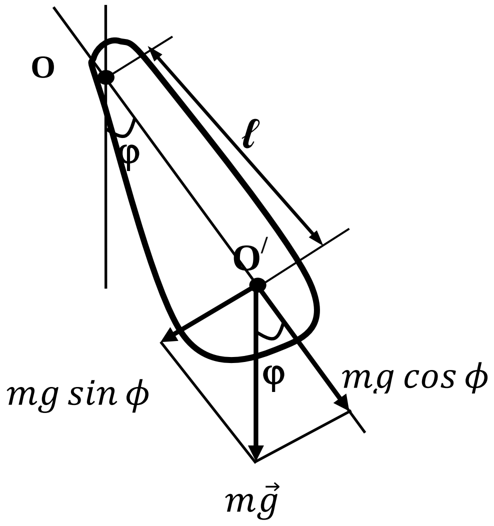


Fig. 4.1.1

As a result of physical pendulum deviation at a certain angle φ from the equilibrium position, due to the force of gravity, arises rotation moment M_{grav}, which seeks to turn the pendulum into equilibrium:

$$M_{\text{grav}} = mg\ell \cdot \sin\varphi, \qquad \text{(Eq. 4.1.1)}$$

where m – pendulum’s mass; g – acceleration free fall; ℓ – distance from the axis of rotation to center of pendulum's mass; φ – the angle of deviation of the pendulum from the equilibrium position.

If pendulum is released in such position, then it'll start make oscillatory movement. Motion of the pendulum is obstructed by air resistance and friction in the pendulum axis. It is known that in the case of a small movement speed, total moment of resistance force M_{res} will be proportional to angular movement speed of the pendulum:

$$M_{\text{res}} = -r\omega = -r\frac{d\varphi}{dt}, \qquad \text{(Eq. 4.1.2)}$$

where r – resistance coefficient of the environment; $\omega = \frac{d\varphi}{dt}$ – angular speed. The “minus” sign indicates opposite directions of vectors $\vec{M}_{\text{res}}$ and $\vec{\omega}$.

According to the main law of rotational motion dynamics:

$$\vec{\beta} = \frac{\sum_{i=1}^{N} \vec{M}_i}{J}. \qquad \text{(Eq. 4.1.3.)}$$

Physical pendulum performs rotational motion under action of two moments of forces M_{grav} and M_{res}. Because of it, equation (Eq. 4.1.3.) after substitutions of moments values of the forces and transformations takes the form:

$$J\frac{d^2\varphi}{dt^2} + r\frac{d\varphi}{dt} + mg\ell\sin\varphi = 0, \qquad \text{(Eq. 4.1.4)}$$

where J – moment of the pendulum inertia, relative to the axis of rotation; β − angular acceleration of the pendulum.

Since oscillation of pendulum are very small oscillations (oscillations with small angles of deviation) for that can be assumed that $\sin\varphi \approx \varphi$.

With addition of $\frac{r}{J} = 2\delta$ and $\frac{\ell mg}{J} = \omega_0^2$, differential equation of physical pendulum's free fading oscillations may take the form:

$$J\frac{d^2\varphi}{dt^2} + 2\delta\frac{d\varphi}{dt} + \omega_0^2\varphi = 0.$$

Solution of this equation is dependence the angle of deviation of the pendulum from the equilibrium position on time:

$$\varphi = Ae^{-\delta t}\cos\left(\omega \mathrm{t} + \varphi_0\right). \qquad \text{(Eq. 4.1.5)}$$

Motion of pendulum can be considered as oscillations with frequency $\omega = \sqrt{\omega_0^2 - \delta^2}$ and amplitude, which varies with time according to the equation:

$$A = A_0 e^{-\delta t}. \qquad \text{(Eq. 4.1.6)}$$

Period of fading oscillations is equal

$$T = \frac{2\pi}{\omega} = \frac{2\pi}{\sqrt{\omega_0^2 - \delta^2}}. \qquad \text{(Eq. 4.1.7)}$$

If resistance coefficient of the environment is small, it can be considered equal to zero (r =0). It leads to fading factor δ=0. Based on it, oscillation period's formula takes the form:

$$T = \frac{2\pi}{\omega} = \sqrt{\frac{J}{mg\ell}}. \qquad \text{(Eq. 4.1.8)}$$

Rate of fading oscillations is characterized by fading factor δ. To determine coefficient of fading, amplitude dependence on time (Eq. 4.1.6) is often used, where amplitude is given in form of a logarithmic function:

$$\ln A = \ln A_0 - \delta t. \qquad \text{(Eq. 4.1.9)}$$

In coordinate system ($\ln A$; t) equation 4.1.9 represents straight line. Value of δ determines angular coefficient of the line's slope to the time axis ***t*** (Fig. 4.1.2):

$$\delta = \frac{\ln\left(\frac{A_0}{A}\right)}{\Delta t}. \qquad \text{(Eq. 4.1.10)}$$

If $\ln(A_0/A)=e=2.71$ then $\delta=1/t_e$.

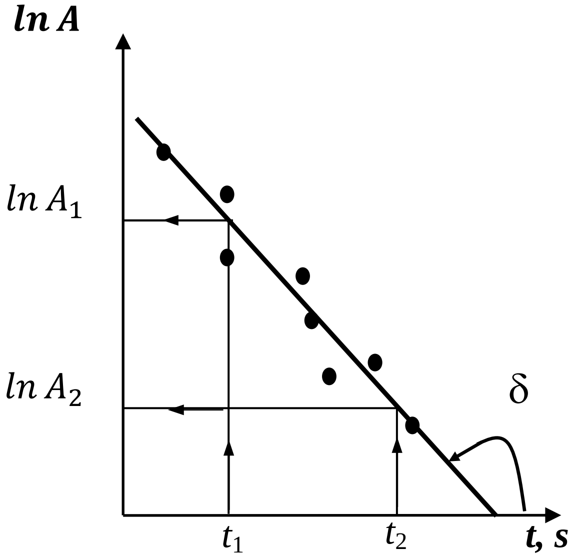


Fig. 4.1.2

So, *fading factor's value* δ is reversed to the time interval t_e, along which amplitude of the oscillations decreases in e=2,71 times.

Relation (Eq. 4.1.9) can be used for experimental determination of δ.

In addition to the fading factor, *logarithmic decrement of fading* χ, is used to characterize them. It is determined by the logarithm of amplitudes ratio, corresponding to the moments of time, that different by period of:

$$\chi = \ln \frac{A_0 e^{-\delta t}}{A_0 e^{-\delta(t+T)}} = \ln e^{\delta t} = \delta \mathrm{T}. \qquad \text{(Eq. 4.1.11)}$$

Period of pendulum oscillations is calculated by the formula:

$$T = \frac{\tau}{N}, \qquad \text{(Eq. 4.1.12)}$$

where τ – is time of N full oscillations finished.

Physical pendulum is made in form of a metal rod *1* (Fig. 4.1.3), with two prisms, attached to the upper end. They are fixated by edges on the frame. To change the oscillation period, a massive weight 2 is placed on the rod. Its position can be adjusted with screws.

Count of the oscillation amplitude is performed in degrees on a scale of 3.

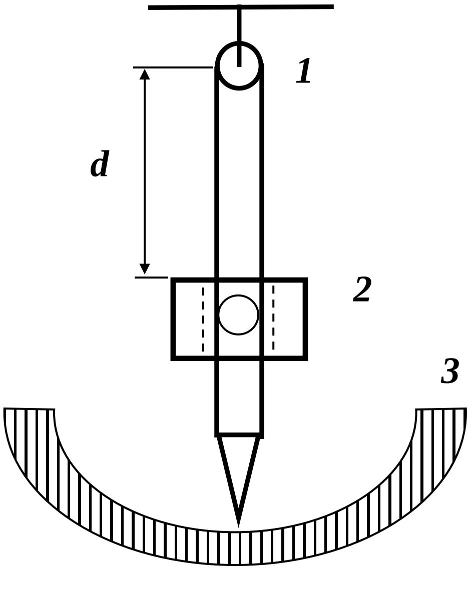


Fig. 4.1.3

Pre-Laboratory Assignment

To perform the work, you need to study such a theoretical material: oscillatory processes and systems; physical pendulum; fading oscillations; characteristics of fading oscillations.

Experimental Procedure

1. Install the weight on the rod to the lowest position possible.
2. Tilt the pendulum at an angle of 8^o–10^o from the equilibrium position and release. Measure time τ of N complete oscillations.
3. Once again, tilt the pendulum at an angle of 8^o–10^o and release it.

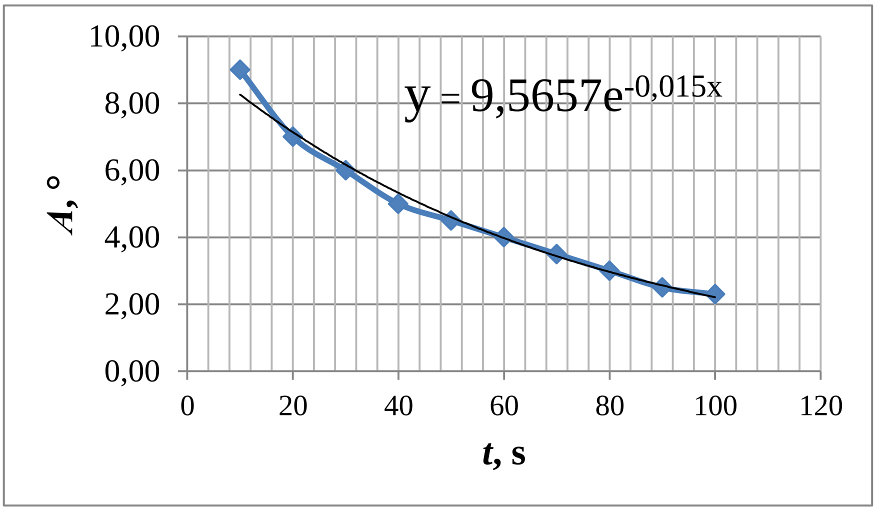
   Every 10-15 seconds determine the amplitude of oscillation A on scale 3 until it decreases to 1^o–2^o.
4. Results of measurements write to Table. 4.1.1, created in Excel.
5. Move the weight to position determined by your teacher, and repeat steps 2-9.

Calculations

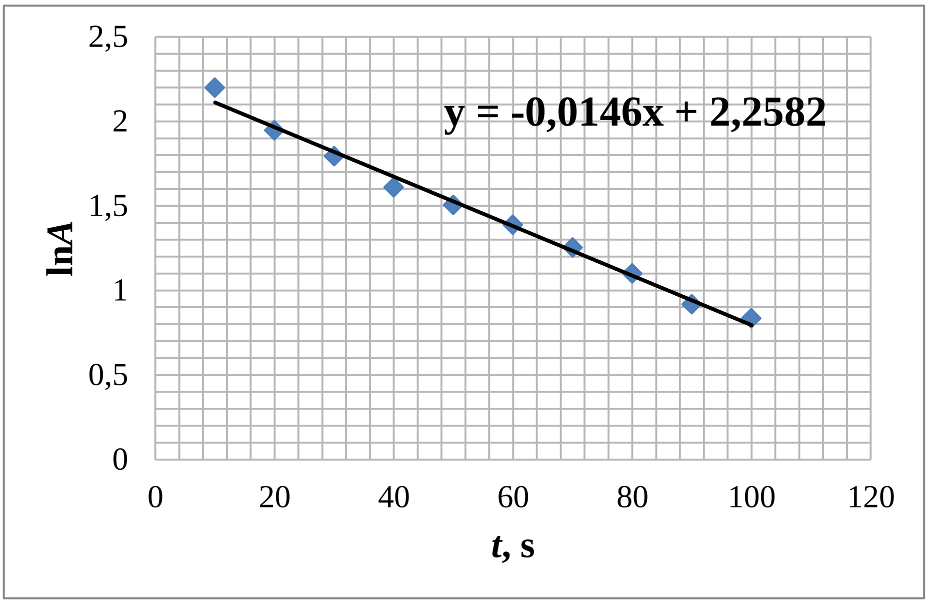
1. Calculate period of the pendulum oscillations by the equation (4.1.12).
2. Construct a dependence graph of the oscillation amplitude A from the time t in Excel (example Graph 4.1). Depict on the graph trend line and its equation, corresponding to the equation 4.1.6.
3. Determine from obtained equation fade factor δ(1) and write its value to Table. 4.1.1.
6. Calculate in Excel value of $\ln A$.
7. Construct a dependency graph $\ln A = f(t)$ (example Graph 4.2). Depict on the graph trend line and its equation, corresponding to the equation 4.1.9.

8. Determine from obtained equation fading factor δ(2) and write its value to the table. 4.1.1.
9. Calculate average value of fading factor δ(avg) and write its value to the Table. 4.1.1.
10. Calculate logarithmic decrement of fading χ with formula (4.1.11), using average value of the fading factor δ(avg).
11. Repeat the same cycle for second position of the pendulum.
12. Make a report in the form of Excel table and graphs.

Graph 4.1



Graph 4.2



Laboratory Report

Data and Calculations Table 6.1.1

τ, s	N	T,s	t, s	A, °	$\delta(1)$, 1/s	ln(*A*)	$\delta(2)$, 1/s	$\delta(\text{avg})$, 1/s	χ

Questions

1. What is oscillation? Describe small oscillations.
2. When oscillations is called free?
3. Describe fading and non-fading oscillations. Depict them.
4. When oscillation is called forced?
5. When oscillations are called harmonic? Write their equation.
6. Give definition of amplitude, phase, initial phase, period, linear and cyclic oscillation frequency.
7. What is a physical pendulum? Name and give definition for other mechanical oscillation systems.
8. Derive differential equations of fading oscillations of physical, spring, and mathematical pendulums. Write their solutions.
9. What is a fading factor, logarithmic decrement of fading? What is their physical meaning?
10. On what does a period of oscillations of physical, spring, and mathematical pendulums depend?

Laboratory 4.2

Research of Oscillatory Circuit Resonance

Objective:

- Study phenomenon of resonance in electric oscillatory circuit, construct resonance curves.
- Determine resonance characteristics of circuit.

Equipment List

- Oscillatory circuit
- Lamp Generator
- Ammeter
- Power supply

Theory

Real electric oscillatory circuit consists of a serial connected capacitor with capacity of C, coil with inductance of L and active resistance R (resistance of connected conductors). After recharging capacitor in the circuit emerges fading electromagnetic oscillations, in other words there is a periodic change in the charge and voltage in the capacitor, and accordingly change of amperage in the circuit.

In this process heat release in active resistance and electromagnetic emission, arise energy losses. To cause and sustain non-stop oscillations, circuit should continuously get energy from an external source, compensating energy loss. It can be done by attaching a triode - an electronic lamp with three electrodes (cathode, anode and a grid).

A scheme lamp-type generator with backward connection is depicted on Figure 4.2.1. To the triode's anode circle are serial connected oscillatory circuit and U_a battery, to the grid circle – coil L_a, *inductively connected to the coil* L from the oscillatory circuit. When voltage U_k, is applied to the cathode, its filament heats, anode amperage generates, and the battery U_a turns on. It results in a short-term amperage in the circle that charges the capacitor: the bottom plate receives a positive charge, the upper one - negative. Then the capacitor is discharged through the coil of inductance L and sinusoidal electrical oscillations arrives in the circuit.

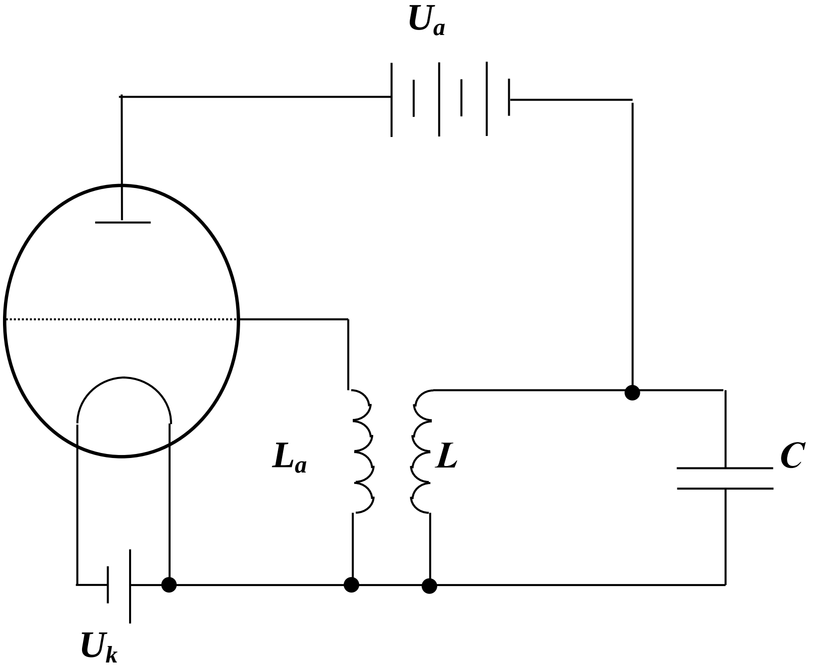


Fig. 4.2.1

However, fading sinusoidal current passing through coil circuit L, creat coil's L_a electromotive force (EMF) of induction, and forms alternating voltage between grid and cathode of the triode. This voltage regulates energy, supplied from the source to the oscillatory circuit.

For the time of negative half-period (when grid has negative potential, and cathode has positive potential) the lamp is «locked» so source U_a does not on. On the contrary (when grid has positive potential, and cathode has negative potential), the source U_a creates an anode potential, given energy for oscillatory circuit. Thus, the oscillations in the circuit will continue. This oscillations are not strictly harmonic, but their difference from the harmonics is such small that it can be neglected.

A system, which itself regulates input of energy into the circuit, is called self-oscillatory, and created in it oscillations – self-oscillations. In self-oscillatory systems, oscillations have constant frequency and amplitude, values of which do not depend on external influence and are determined by properties of the system.

In addition to generators based on electronic lamps, are widely used semiconductor generators of electrical oscillations based on transistors. They are similar in structure, but have significant advantages in comparanse with lamp-based: have no heating cathodes, do not consume significant energy, and do not requiring time to heat up; works at lower voltages; have significantly smaller sizes and so on.

In self-oscillatory systems (not only electromagnetic), under certain conditions, may occur resonance.

Phenomenon of resonance in a oscillatory circuit consists of quick increase in amplitude of forced oscillations current or voltage in the circuit, with approaching of external EMF frequency ω to thenatural frequency of oscillation ω_0.

Simplest oscillations of this type can be created by inductive connection of circuit inductance coil L with external coil L_a, which has alternate amperage flow. If induced in the circuit If EMF of induction change according the law $\varepsilon = \varepsilon_0 \sin\omega t$, so *differential equation of forced oscillations* takes the form:

$$L\frac{d^2q}{dt^2} + R\frac{dq}{dt} + \frac{1}{C}q = \varepsilon_0 \sin\omega t, \qquad \text{(Eq. 4.2.1)}$$

where L − inductance of coil, C − capacity, R − active resistance.

Based on the fact, that frequency of circuit's oscillations $\omega = 1/\sqrt{LC}$, and damping factor $\delta = R/2L$, equation (4.2.1) takes the form:

$$\frac{d^2q}{dt^2} + 2\delta\frac{dq}{dt} + \omega_0^2 q = \varepsilon_0 \sin\omega t. \qquad \text{(Eq. 4.2.2)}$$

Solutions of the equation for voltage amplitudes U_{max} on capacitor and current I_{max} in the circuit:

$$U_{max} = \frac{\varepsilon_0}{\frac{\omega}{\omega_0^2}\sqrt{\left(\frac{\omega_0^2}{\omega} - \omega\right)^2 + 4\delta^2}}, \qquad \text{(Eq. 4.2.3)}$$

and

$$I_{max} = \frac{\varepsilon_0}{L\sqrt{\left(\frac{\omega_0^2}{\omega} - \omega\right)^2 + 4\delta^2}}. \qquad \text{(Eq. 4.2.4)}$$

Graphs of corresponding functions $U_{max} = f(\omega)$ (Eq. 4.2.3) and $I_{max} = f(\omega)$ (Eq. 4.2.4) are depicted on Fig. 4.2.2 and Fig 4.2.3.

According to the graphs, amplitudes of the voltage and amperage sharply increases quickly in case of external EMF frequency ω approaches to value of the circuit's oscillations frequency ω_0. Should be emphasized, that *resonance frequency* ω_{res} (frequency for maximal amplitude of voltage and amperage) for amperage I_m matches with the its own oscillations frequency ω_o in case of no fading. For voltage U_m resonance frequency depends on:

$$\omega_{res} = \sqrt{\omega_0^2 - 2\delta^2}, \qquad \text{(Eq. 4.2.5)}$$

and decreases with increase of damping factor.

The peculiarity of both graphs (Fig. 4.2.2, Fig 4.2.3) is that as the magnitude of the damping increases, the width of the resonance curve increases and its height decreases. Quantitative characteristic of resonant curve shape is Q - factor, which characterizes loss of energy in the circuit, and by definition is equal to π/χ where χ – logarithmic decrement of free oscillations fading in the circuit. Q - factor shows how many times the capacitor voltage amplitude at resonance exceeds the external EMF amplitude.

In addition, the circuit's, corpulence characterizes peak of resonance curves. This can be seen in Figur 4.2.3, which shows the width of the resonance curve for the current at half the maximum power. According to the Joule-Lenz law, power in the circle is proportional to amperage squared.

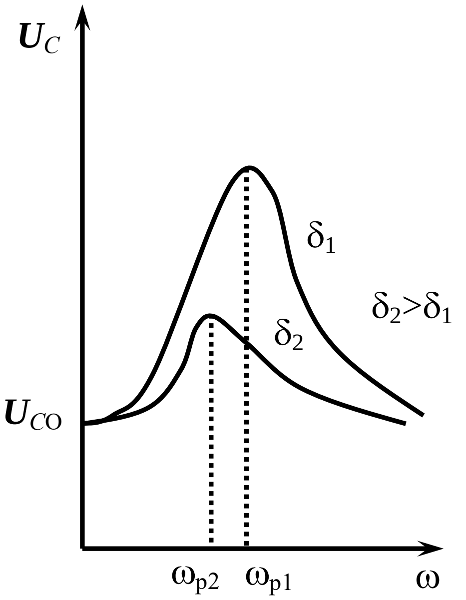


Fig. 4.2.2

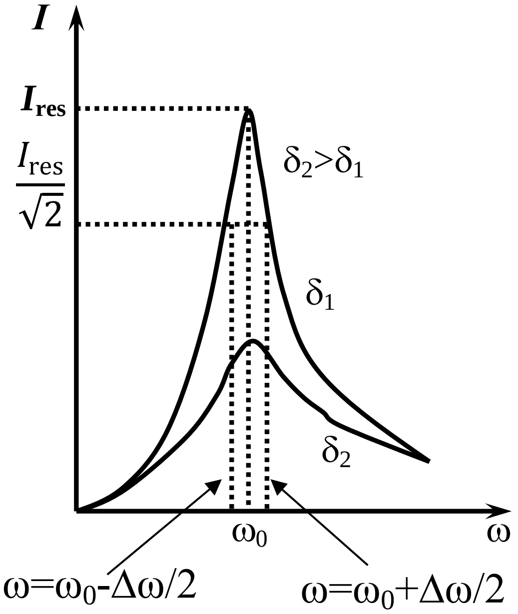


Fig. 4.2.3

This means that when the current in the circuit decreases $\sqrt{2}$ times relative to the maximum value, the power is halved. In the case of small damping, it can be shown that this occurs when the frequency ω of the external EMF deviates from the magnitude ω_0 of the damping factor δ.

The width of the resonance curve $\Delta\omega$ (or the bandwidth of the oscillating circuit) has relationship with the Q - factor:

$$Q = \frac{\omega_0}{\Delta\omega}. \qquad \text{(Eq. 4.2.6)}$$

The installation diagram is shown in Fig. 4.2.4.

This laboratory uses a tube generator that is inductively coupled to the oscillating circuit and is controlled by the P1 slider. Oscillation frequency of the generator can be regulated with P_2 switch. It's range 0,7 ... 1,4 MHz. Value of the oscillatory circuit's capacitor can be changed with P_3 switch.

Resonance can be achieved by setting of the corresponding value capacity C of the capacitor, and rotating switch P_2 of the generator. You'll get confirmation flash of lamp L (Fig. 4.2.4).

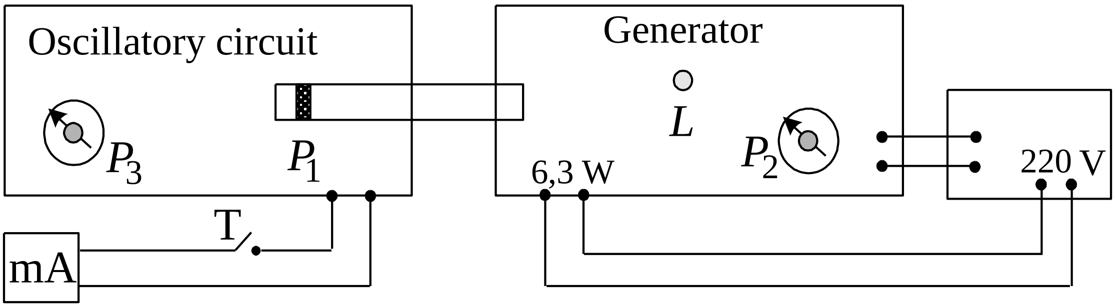


Fig . 4.2.4

Pre-Laboratory Assignment

To perform the work, you need to study such a theoretical material: free fading oscillations; forced oscillations; resonance; forced electromagnetic oscillations in electric oscillatory circuit; self-oscillatory systems. Please read the instructions from Laboratory 3.8, 4.1 before performing the work.

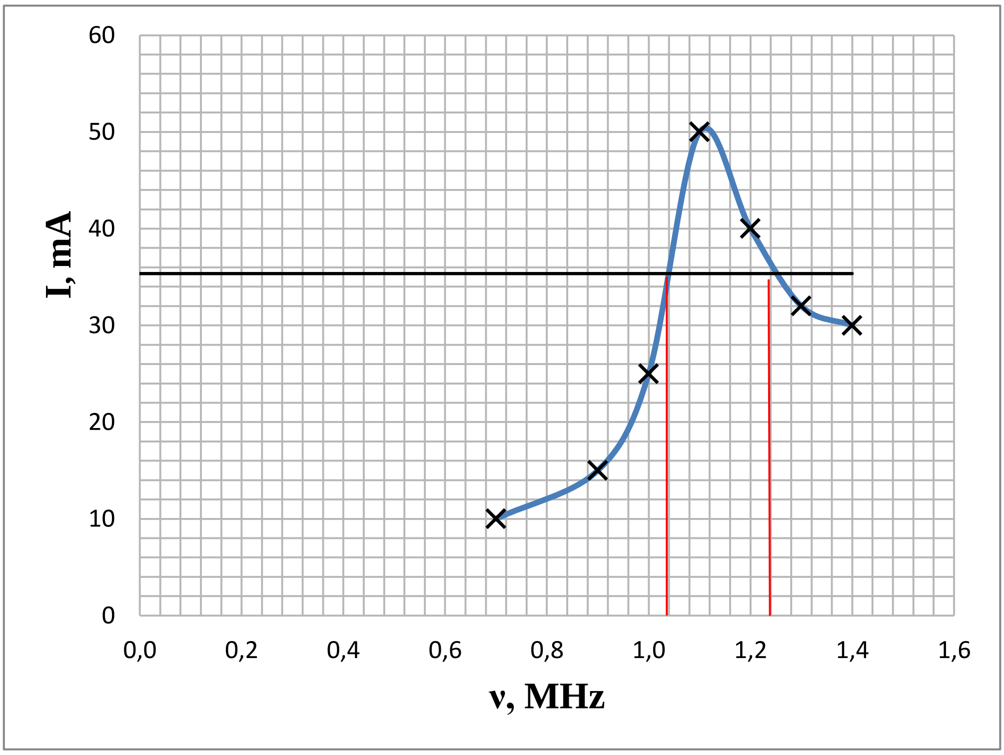
Experimental Procedure

1. Before switching on the appliance, make sure that the inductive connection of the generator with the circuit is minimal, ie the slider P1 is in the far left position and the toggle switch T, which switches on the milliammeter, is in the "On" position.
2. Set the capacitance switch P_3 of the oscillating circuit to the appropriate position, and the frequency switch P_2 of the oscillator to the leftmost position.
3. Switch on the appliance and wait 2 minutes for the lamp cathode to warm up. The readiness of the instrument to work is that the galvanometer will start recording current.
4. Turn off the milliammeter.
5. Set capacitance of the capacitor C_1 (given by teacher) by the switch P_3. Set an inductive connection between the oscillation circuit and the generator, then move slider P_1 to the extreme right position.
6. Turn frequency switch P_2 to achieve lamp L signal. Record value of resonant frequency ν_{res1} for capacitance C_1.
7. Move slider P_1 to the extreme left position (inductor connection of the generator with the circuit is minimal) and turn on the milliammeter. Change values of the generator frequency ν, record their corresponding values of amperage I. Data of measurements put to table. 4.2.1.
8. Repeat steps 4-6 for two capacitance values (given by teacher).
9. Write in Excel Table 4.2.1 all results of mesurment.

Calculations

1. Using obtained data, construct resonant curves $I = f(\nu)$ in the Excel (Graph example 4.2).
2. Determine Q - factor of the oscillatory circuit. To do this:
   - i) On the graphic $I = f(\nu)$ draw a straight line parallel to the frequency axis at the level $I_{res}/\sqrt{2}$;
   - ii) project intersection points to the frequency axis;
   - iii) determine corresponding frequencies ν(1) and ν(2) (Graph example 4.2).
3. Repeat step 2 for two more capacitor capacitance values.
4. Calculate width of the resonance curves $\Delta\omega = 2\pi\Delta\nu$.
5. Calculate corpulence of the oscillatory circuit for each value of capacity according to the equation 4.2.6, where $\omega_0 = 2\pi\nu_{res}$.
6. Make a report in the form of Excel table and graphs.

Graph



Laboratory Report

Data and Calculations Table 6.3.1

C	ν(res), MHz	ν, MHz	I, mA	$\nu(1)$, MHz	$\nu(2)$, MHz	$\Delta\omega$, rad/s	Q

Questions

1. What makes an electric oscillatory circuit?
2. Explain the emergence of electromagnetic oscillations in an electromagnetic oscillation circuit.
3. How does a lamp generator of continuous oscillations work?
4. Describe self-oscillatory system.
5. Describe energy transformation in electromagnetic oscillatory circuit.
6. Describe resonance phenomenon.
7. Derive differential equation of forced oscillations in the electric oscillatory circuit.
8. How does the oscillatory circuit capacitor voltage and the amperage depends on the frequency of external EMF?
9. What is the value of resonance frequency for the amperage in the circuit, and the voltage on the capacitor?
10. What is a corpulence of oscillatory circuit?
11. How does a bandwidth of oscillatory circuit depend on the value of its resistance?
12. Make a block diagram of electric self-oscillating system and explain how it works.

Laboratory 4.3

Determination of the Sound Speed in the Air by the Method of Standing Waves

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Objectives:

- Investigate the processes propagation of oscillations in a continuous medium.
- Conditions for the emergence of standing waves.
- Determine the speed of sound in the air.

Equipment List

- Sound source
- Cylindrical tube
- Ruler
- Battery

Theory

Wave (wave process) is the process of propagation of oscillations in space. The process of propagation in the space of vibrations of particles of a continuous elastic medium, continuously distributed in space, called *mechanical (elastic) wave*. The deformation that occurs in some place causes the initial deviation of the medium particles from the equilibrium position, and the presence of elastic forces between the particles of the medium predetermines the process of transfer of the vibrational state from one particle to another.

When the wave propagates, the particles of the medium do not move with the wave, but only oscillate around their equilibrium positions. Together with the wave from the particle to the particle of the medium, only the state of vibrational motion and its energy are transmitted. *The main property of all waves is energy transfer without matter transfer.*

There are *longitudinal* and *transverse* mechanical waves. In longitudinal waves, the medium particles oscillate along the direction of wave propagation, they occur due to compression and tension deformations, that is, in solids, liquids and gases. In transverse waves, the particles of the medium oscillate perpendicular to the direction of wave propagation, such waves are formed due to shear deformation, which is possible in solids and at the boundary of the distribution of two media (e.g. waves on the surface of water).

Sound is called mechanics waves of small amplitude, the frequencies of which lie in the range from 16 to 20000 Hz. Waves with a frequency less than 16 Hz, called *infrasound*, with a frequency greater than 20000 Hz - -*ultrasound*.

Waves carrying energy in space are called propagation waves. The equation of the propagation flat elastic wave has the form:

$$\xi_1 = A\cos\left(\omega t + kx\right),$$

where ξ_1 – displacement, A – wave amplitude, $\omega = 2\pi\nu$ − cyclic frequency, $k = 2\pi/\lambda$ − wave number, x – distance from the sound source.

The equation of the wave reflected from some obstacle and propagating towards (reflected), has the form:

$$\xi_1 = A\cos\left(\omega t + kx\right).$$

As a result of superposition of a direct and reflected wave, a standing wave appears, the equation of which has the form:

$$\xi = \xi_1 + \xi_2 = 2A\cos kx \cdot \cos\omega t,$$

where $2A\cos kx$ − the amplitude of the standing wave, what depends on the coordinate x.

The last expression shows that in some points of space the amplitude of oscillations is zero. These points are called *nodes of the standing wave*. The points at which the amplitude of the standing wave reaches its maximum value are called *antinodes*. The coordinates of the nodes and antinodes of the standing wave can be obtained from the expression for the amplitude of the standing wave:

$$x_n = (2m+1)\frac{\lambda}{4}, \qquad \text{and} \qquad x_a = m\frac{\lambda}{4},$$

where $m = 0, 1, 2, ...$

As can be seen from these formulas, the distance between adjacent nodes or antinodes is (Fig. 4.3.1, *b*):

$$\Delta x = \frac{\lambda}{2}. \qquad \text{(Eq. 4.3.1)}$$

The difference between the standing wave and the *transverse* wave is that there is *no energy transfer* in a standing wave.

The picture of the standing wave in an air column of a pipe of different length is represented on figure 4.3.1. As can be seen from the figure, in all cases, when the standing wave is formed, the piston P is a node, and at the open end-antinode (Fig. 4.3.1, a). It should be notied that as a result of the superposition of a direct and reflected wave, the standing wave is not always formed. For the pipe, closed at one end, should meet the following condition: the distance between the piston and the source of the sound (Fig. 4.3.1, a) must be a multiple $\lambda/4$.

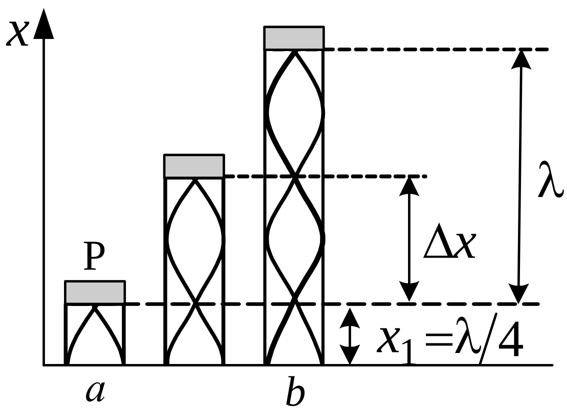

Fig. 4.3.1

For all transverse waves, the ratio is true:

$$\upsilon = \lambda \cdot \nu, \qquad \text{(Eq. 4.3.2)}$$

where υ − the speed of wave propagation, λ − the wavelength, ν − the frequency of oscillations.

Consequently, the definition of the speed of sound is reduced to the determination of the wavelength λ. As can be seen from the equation (4.3.1) and fugure 4.3.1, the wavelength is twice the distance between adjacent wave antinodes:

$$\lambda = 2\Delta x. \qquad \text{(Eq. 4.3.3)}$$

The speed of sound propagation depends on the temperature of the medium. For air:

$$\upsilon = \sqrt{\gamma \frac{RT}{\mu}}, \qquad \text{(Eq. 4.3.4)}$$

where $\gamma = C_p / C_V$ − ratio of specific heats (for air $\gamma = 1.4$); $\mu = 0.029$ kg / mol − molar mass of air.

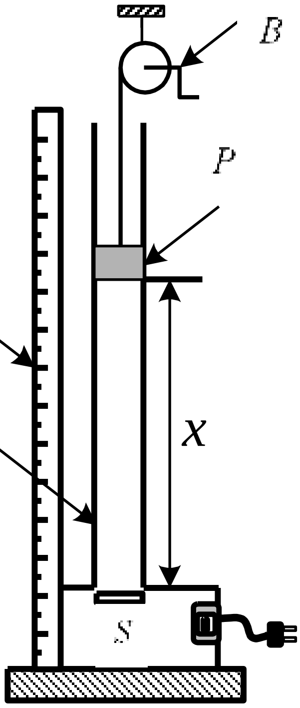

Fig. 4.3.2

At $t = 0$ °C and according to the equation (4.3.4), air velocity $\upsilon = 330$ m / s, and at room temperature $t = 17$ °C – $\upsilon = 340$ m/s.

The diagram of this investigation is shown in Figure 4.3.2, and consists of a cylindrical tube *T*, closed on one side by a piston connected to the moving bloke *B*.

The bottom of the tube is near the open end of the sound source *S* – the sound oscillator (the frequency indicated on the installation). The coordinates of the points of the antinodes are measured using a ruler *R*.

Pre-Laboratory assignment

To perform the work, you need to study such a theoretical material: frequency and period of oscillation, transverse and longitudinal waves, velocity of elastic waves, standing wave, vibrations of a string; speed of sound in gases. Before completing work read instructions for *Laboratory* 4.1.

Experimental Procedure

1. Turn on the generator power of sound oscillation S.
2. Rotating the knob B of the unit would slowly raise the piston while the volume of the sound will change periodically.
3. Measure several the positions of the piston when the volume of sound reaches the maximum value.
4. The measurement results record to table 4.3.1 in Excel.

Calculation

1. Calculate the distance $\Delta x = x_{i+1} - x_i$ between two adjacent piston positions where the volume reaches the maximum.
2. To calculate the average value Δx_{av}.
3. By equation (4.3.3) find the wave length λ of the sound.
4. By equation (4.3.2) find the speed of sound in the air υ_{exp}.
5. Calculate the temperature in the room at the time of the experiment by the equation (4.3.4).
6. Determine the actual room temperature at the time of the experiment and calculate υ_{theory} by the equation (4.3.4).
7. Make a report in the form of Excel table and graphs.

Laboratory Report

Data and Calculations Table 6.3.1

x_i, m	Δx m	Δx_{av}, m	λ, m	ν, Hz	υ_{exp}, m/s	γ	R, J/(kg·K)	μ, kg/mol	T_{exp}, K	t_{exp}, °C	t, °C	T, K	T_{theory}, m/s

Questions

1. Give the definition of the wave process.
2. What waves are called elastic?
3. Give the definition of longitudinal and transverse waves.
4. Derive the equation of a plane monochromatic sine wave traveling.
5. What is called wavelength? Write down the formula for the relationship between wavelength and frequency.
6. What parameters can determine the speed of sound in gases?
7. What is standing wave? Write down its equation.
8. What is the knot and the antinode of a standing wave? Determine their mutual placement.
9. What is sound, infra-and ultrasound? Give examples of the use of ultrasound.

Laboratory 5.2

Determination Wave Lengths of Light Using a Diffraction Grating

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Objective:

- Study the phenomenon of diffraction.
- Determine light wave length with using a diffraction grating.
- Determine thickness of a human hair from a diffraction pattern.

Equipment List

- Laser
- Diffraction grating
- Yardstick

Theory

Diffraction refers to phenomena associated with wave bending around obstacles encountered in their path, or, in a broader sense, phenomena associated with any deviation of the laws of geometric optics in the process of light spreading. To explain the diffraction phenomenon, Huygens formulated the principle that each point in space, to which the wave front reaches, becomes the center of secondary coherent waves, and the envelope of these waves gives the position of the wave front at the next time.

Fresnel supplemented Huygens’ principle with the idea of interference of secondary waves. He proposed to divide the spherical wave front into zones so that the distance from the edges of the zones (coherent wave sources) to the observation point M (Fig. 5.2.1) differed by λ/2.

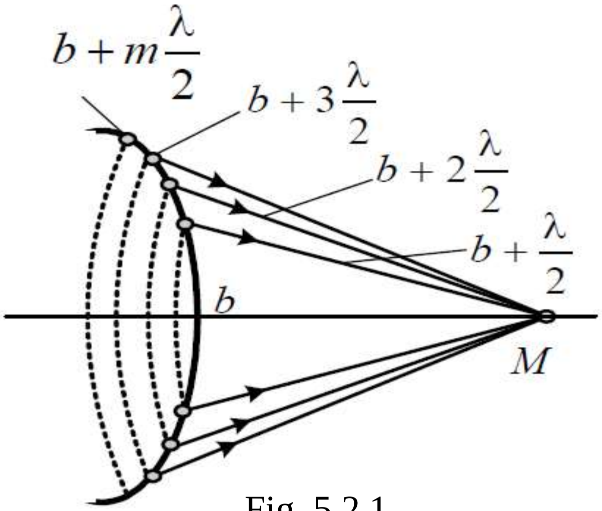

Fig. 5.2.1

Then depending on the number of zones of *m* at the point M, amplification or weakening of the intensity of the waves may be observed at their superimposition.

If the width of the obstacle (for example, the slit) is *b*, the distance from it to the observation point is *l*, and the wave length is λ, then the parameter $b^2/(\lambda l)$ determines the number of Fresnel's zones *m*, which opens this obstacle. So, diffraction can be observed only when m << 1 (Fraunhofer's diffraction), or m ~ 1 (Fresnel's diffraction). If m >> 1, then the laws of geometrical optics are confirmed.

The greatest practical importance is diffraction, which is observed in parallel rays (Fraunhofer's diffraction) with light passing through one-dimensional diffraction gratings (Fig. 5.2.2).

Diffraction gratings are a system of parallel slits of the same width, which lie in the same plane and are separated by equal width in opaque slits. If *a* is the width of the opaque part, and *b* is the width of the transparent part, then the sum $d = b + a$ is called the constant (period) of the diffraction grating.

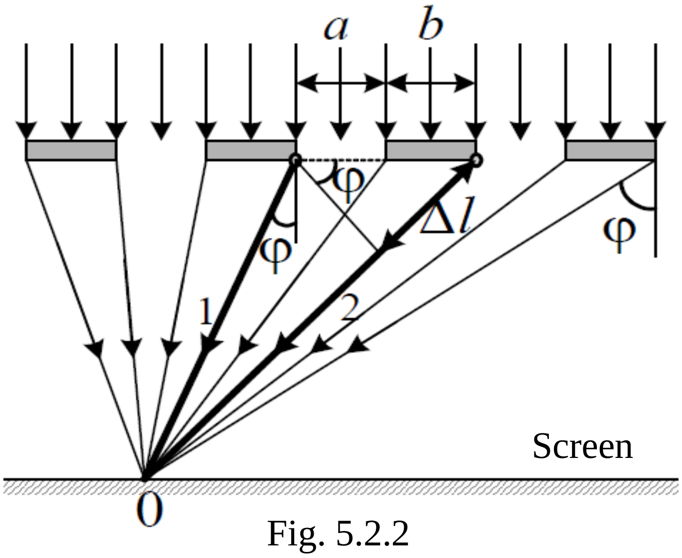

Fig. 5.2.2

If the number of transparent slits of the grating per unit length l is N (the number of primes), then the diffraction grating constant is found from the correlation:

$$d = \frac{l}{N}. \qquad \text{(Eq. 5.2.1)}$$

Let a plane light wave (Fig. 5.2.2) fall onto a diffraction grating. According to the Huygens-Fresnel's principle, each point of this front is a source of secondary spherical coherent waves. As a result, all points of each slit emit spherical waves. Take, for example, the points lying at the edges of all slits and consider the rays emerging at an angle φ to the direction of spreading of a plane wave (the diffraction angles φ will be considered small). The illumination at point 0 on the screen will be the result of the interference of all the rays. Fig. 5.2.1 shows that between the rays 1 and 2 there is the path difference:

$$\Delta l = (a + b) \cdot \sin\varphi = d \cdot \sin\varphi.$$

If the integer wave length fits in in the path difference, interference maximum arises. Thus, the condition of the main diffraction maxima is:

$$d \cdot \sin \varphi = m\lambda, \qquad \text{(Eq. 5.2.2)}$$

where d – grating constant; φ – diffraction angle; m – order of the diffraction maximum; λ – light wave length.

Part 1

If the diffraction angles are small (Fig. 5.2.3), then $\sin \varphi \approx \tan \varphi$, i.e.

$$\tan \varphi = \frac{l_m}{L}. \qquad \text{(Eq. 5.2.3)}$$

Judging by equation (5.2.2) and (5.2.3) the wave length is:

$$\lambda = \frac{d \cdot l_m}{m \cdot L}, \qquad \text{(Eq. 5.2.4)}$$

where l_m – distance from the central maximum to the diffraction maximum of the m-th order; L – distance from the diffraction grating to the screen.

In this laboratory work, the light source is an optical quantum laser generator (laser). Diagram of the laboratory equipment is shown in Fig. 5.2.3. The laser radiation (laser) passes through the diffraction grating DG and creates a diffraction pattern on the screen S.

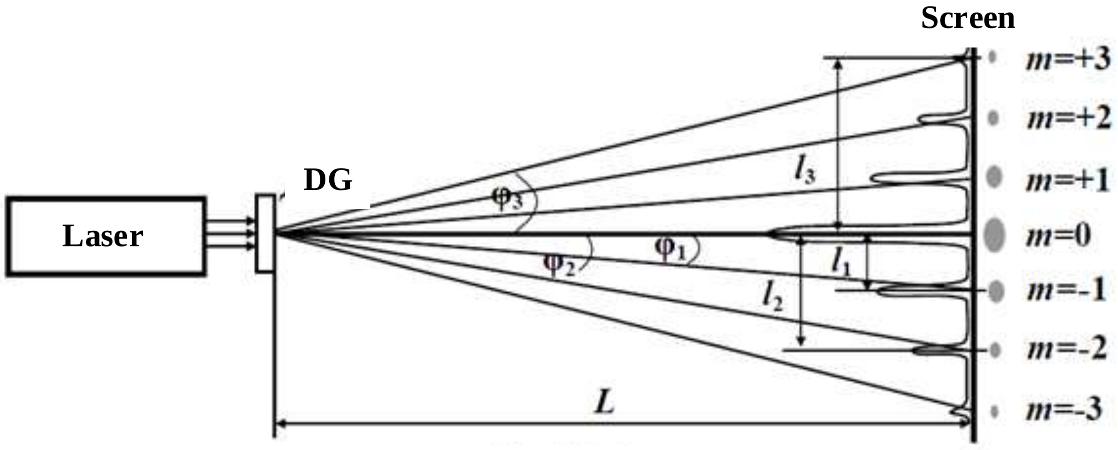

Fig. 5.2.3

Pre-Laboratory Assignment

To perform the work, you need to study such a theoretical material: wave diffraction; parallel diffraction; diffraction gratings and their characteristics.

Experimental Procedure for Part 1

1. According to the instructions turn on the laser.
2. Set diffraction gratings in the path of the laser ray with known the number of primes N.
3. Determine the number of primes N per unit length for each diffraction grating.
4. Observing the diffraction pattern on the screen, measure the distances l_1, l_2, l_3 from the central maximum ($m = 0$) to the maximum of the first, second and third order ($m = 1, 2, 3$).
5. Determine the distance from the grating to screen L.
6. Include the measurement results in Table 5.2.1 in Excel.
7. Perform operations 2-3 for different diffraction gratings (given by the teacher).

Calculations for Part 1

1. Calculate the constant d of the diffraction grating by the equation (5.2.1).
2. Calculate the wave length of the light by the equation (5.2.4) for each measurement l_m for all types of the gratings.
3. Calculate the average wave length $<\lambda>$ for all types of the gratings.
4. Calculate the average wave length $<\lambda>$.
5. Make all calculations in Excel and include them in Table 5.2.1.
6. Make a report in the form of Excel table and graphs.

Laboratory Report for Part 1

Data and Calculations Table 5.2.1

Type of a grating		Distance to maxima			L, m	λ, m	$<\lambda_1>$, μm	$<\lambda>$, μm
N_1	d_1, m	l_1, m	l_2, m	l_3, m				

Part 2

The second part of the laboratory work is based on the diffraction phenomenon, which occurs as a result of insertion a thin obstacle (for example, a human hair) with thickness b into a parallel laser ray. The path of the rays in this case is shown in Fig. 5.2.4.

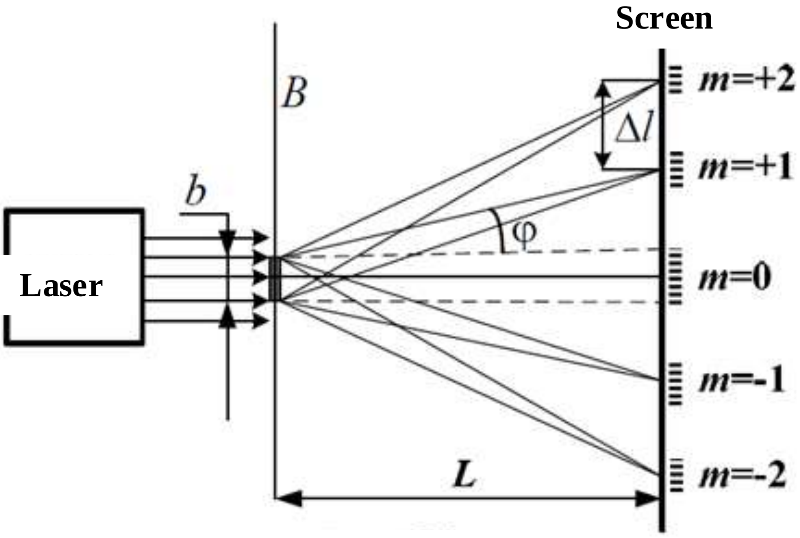

Fig. 5.2.4

The laser radiation passes through a hair B and forms a diffraction pattern on the screen S. Formula (5.2.2) for the case of diffraction on a single obstacle of width b (thickness of a hair) is:

$$b \cdot \sin\varphi = m\lambda. \qquad \text{(Eq. 5.2.4)}$$

From (Eq. 5.2.2) and (Eq. 5.2.3) it follows that:

$$b \cdot \frac{l_m}{L} = m\lambda, \qquad \text{(Eq. 5.2.6)}$$

where l_m – distance from the central maximum to the diffraction maximum of the *m*-th order.

Writing (5.2.6) for the two nearby maxima and subtracting one equation from another one, we obtain the formula for calculating thickness of a hair:

$$b = \frac{\lambda \cdot L}{\Delta l}, \qquad \text{(Eq. 5.2.7)}$$

where λ – laser radiation wave length, the value of which is taken from the results of calculations performed in the first part of the work;

L – distance from a hair to the screen;

Δl – distance between two nearby maxima or minima of the diffraction pattern $\Delta l = l_{m+1} - l_m$.

Experimental Procedure for Part 2

1. Fasten a hair perpendicular to the ray of the laser.
2. Measure the value of Δl between nearby maxima of different orders of maxima *m* three times on the screen. For each measurement of Δl_m, calculate the value of *b* by the equation (5.2.7) and find the average value of <*b*> in micrometers.
3. Write the results of measurements in Excel Table 5.2.2.

Calculations for Part 2

1. For each measurement of Δl_m, calculate the value of *b* by the equation (5.2.7).
2. Find the average value of <*b*> in micrometers.
3. Make a report in the form of Excel table and graphs.

Laboratory Report for Part 2

Data and Calculations Table 5.2.2

Distance between maxima			L, m	λ, m	$\langle b \rangle$, μm
Δl_1, m	Δl_2, m	Δl_3, m			

Questions

1. What is diffraction?
2. Formulate the Huygens-Fresnel's principle.
3. What is coherence, temporal and spatial coherence?
4. What waves are called monochromatic?
5. What is the difference between Fraunhofer's diffraction and Fresnel's diffraction?
6. What are diffraction gratings? Name characteristics of a diffraction grating.
7. What is the geometric and optical path difference of rays? Build the ray path during Fraunhofer's diffraction and show the path difference of the rays.
8. Record the conditions for diffraction maxima and minima. Explain the occurrence of a diffraction spectrum in white light.

Laboratory 5.3

Polarized Light Research

Objective:

- Study the phenomenon of light polarization and methods for producing polarized rays.
- Check the Malus law.
- Determine the degree of polarization of laser radiation.

Equipment List

- Laser
- Analyzer

Theory

The effect of light on the medium is mainly due to *the vector of the electric field strength* of the electromagnetic wave, therefore in optics this vector is called *a light vector*. If in each wave train a light vector has a predominant oscillation direction, then the light is called polarized light in contrast to unpolarized or natural light, for which any direction of oscillation of the light vector is equally probable.

When a light beam propagates perpendicular to the page plane, the main cases of possible orientations of a light vector are shown schematically in Fig. 5.3.1. In Fig.5.3.1 (*a*) natural light is shown, in Fig. 5.3.1 (*b*) partially polarized light is shown (a light vector oscillates mainly in the vertical plane), and Fig. 5.3.1 (*c*) corresponds to linearly polarized light (a light vector oscillates only in one plane rigidly fixed in space).

If unpolarized light becomes polarized when passing through an optical device, then this device is called *a polarizer*. The plane of the polarizer is the plane in which the light vector of the beam oscillates at the exit of the polarizer.

A polarizer is also used to analyze the state of polarization of light. In this case, it is called an analyzer.

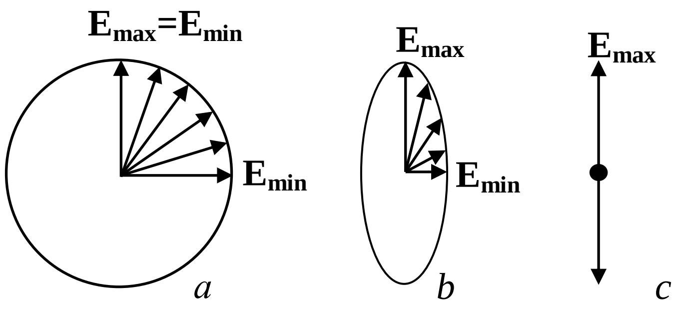

Fig. 5.3.1

If the planes of the polarizer and analyzer form an angle α, then in the case of falling onto the analyzer a light intensity I_0, a light beam of intensity I will be obtained (*Malus law*):

$$I = I_0 \cdot \cos^2 \alpha \qquad \text{(Eq. 5.3.1)}$$

Let partially (elliptically) polarized light fall on the analyzer. If the analyzer rotates, then according to the Malus law, the light intensity at the output will vary from $I_{\max}$ (the plane of polarization of light is parallel to the plane of the analyzer) to $I_{\min}$ (the plane of the analyzer is perpendicular to the plane of polarization of light). The state of polarization of light is characterized by the degree of polarization:

$$k = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \cdot 100\%. \qquad \text{(Eq. 5.3.2)}$$

For linearly polarized light, $k = 1$, for natural light, $k = 0$, and in the case of partially polarized light, $0 < k < 1$.

The most common are polarizers, the principle of which is based on the phenomenon of anisotropy and optical dichroism. As is known, in anisotropic crystals only linear and extraordinary rays linearly polarized in mutually perpendicular planes can propagate. In optically dichroic crystals, the absorption coefficient of one of the rays is so large that this beam is almost completely absorbed in the order of ten microns and virtually linearly polarized light comes out of the crystal. *Polaroid* are two glasses between which a thin layer of optically dichroic microcrystals, oriented in the same direction, is placed.

The Malus law is studied on the installation, the scheme of which is shown in Fig. 5.3.2. The source of linearly polarized light is a laser, one of the elements of which is a polarizer mounted at *Brewster angle*. The laser beam passes through the analyzer (polaroid) A and enters the photodetector F. Under the influence of light, photo-EMF is generated in the photodetectors, and therefore the galvanometer G connected to it captures a current proportional to the light intensity.

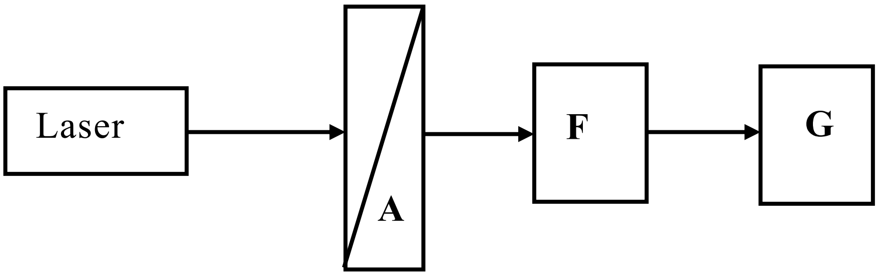

Fig.5.3.2

Pre-Laboratory Assignment

To perform the work, you need to study such a theoretical material: light polarization; light polarization during reflection and refraction at the boundary of two dielectrics; birefringence in crystals; Malus law; polarizing devices.

Experimental Procedure

1. According to the instructions turn on the laser.
2. Set the analyzer to its initial position (0°) and include the measurement result of the current I in Table 5.3.1.
3. Determine the current in the range of angles 0 ... 360°, each time turning the analyzer through an angle of 15°. Include the measurement results in Table. 5.3.1.
4. Turn off the laser.

Calculations

1. Plot the dependence $I = f(\alpha)$, using the received data.
2. Define $I_{\max}$ and $I_{\min}$ from the graph.
3. Calculate the degree of polarization by the equation (5.3.2).
4. Calculate the function $I = I_{\max}\cos^2\alpha$ in the range of angles 0 ... 360° and mark the corresponding points on the experimental graph.
5. Make all calculations in Excel and include them in Table 5.3.1.
6. Make a report in the form of Excel table and graphs.

Laboratory Report

Data and Calculations Table 5.3.1

α°	0	15	30	45	60	75	90	105	120	135	150	165	180
I, μA													

α°	195	210	225	240	255	270	285	300	315	330	345	360
I, μA												

Questions

1. What is light?
2. What is called light polarization?
3. What is non-polarized, plane-polarized, partially polarized and circularly polarized light?
4. What are the methods for producing plane-polarized light? What polarization devices work on their basis?
5. Write down the Brewster law. What is called the Brewster angle?
6. What is a polarizer and analyzer?
7. What is the degree of polarization of partially polarized light?
8. Write down the Malus law and explain it.
9. Give examples of the application of the polarization phenomenon.

Laboratory 5.6

Determination of Work function of an Electron by Method of Stopping Potential

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Objective:

- Study the basic laws of the external photoelectric effect.
- Determine work function of photoelectron and the maximum speed of photoelectrons.

Equipment List

- Light source
- Variable light filter
- Photocell
- Voltmeter
- Galvanometer

Theory

The *photoelectric effect* (photoeffect) is a process of interaction of electromagnetic radiation with substance by which the photon energy is transferred to the electrons of the substance. There are two types of photoeffect: external and internal photoelectric effect. The *external photoelectric effect* is a process in which an electron, under the influence of radiation, extends beyond the surface of a substance, while the internal one only leads to an increase in the number of free electrons inside the substance.

For the first time, Roentgen drew attention to this phenomenon, Stoletov investigated and established the corresponding laws, and Einstein gave a theoretical justification of the external photoeffect based on the quantum theory of light

(Planck's hypothesis), according to which light is emitted and absorbed by substance in separate portions – quanta (or photons). The photon energy, which corresponds to a light wave with a frequency ν (wave length λ), is determined by the formula: $\varepsilon = h\nu = \frac{hc}{\lambda}$, where h is the Planck constant; c is the speed of light in vacuum; λ is the wavelength of light.

When a photon beam falls on a metal surface, a photon interacts with an electron, as a result of which the photon gives up all its energy to the electron. If this energy exceeds the work function of the electron from the metal (Φ), then the electron leaves the substance and has a certain kinetic energy. Kinetic energy will be maximum when the electron, leaving the metal, does not lose energy in a collision with the crystal lattice and other electrons.

Then, according to the law of conservation of energy, *Einstein's formula for the external photoelectric effect* will look like this:

$$h\nu = \Phi + \frac{m\upsilon_{max}^2}{2}, \qquad \text{(Eq. 5.6.1)}$$

that is, the energy of a photon as a result of interaction with an electron is completely spent on "tearing" the electron from the surface of the substance and providing it with kinetic energy.

Equation (5.6.1) is called the Einstein's equation for the external photoelectric effect and explains all its basic laws (*Stoletov's laws*):

- *first*: the saturation photocurrent does not depend on the frequency of the light incident on the substance, but is determined only by its intensity;
- *second*: the maximum speed of photoelectrons depends on the frequency of light and does not depend on its intensity;

- *third*: there is a red border of the photoelectric effect, that is, such a maximum wavelength (or minimum frequency) at which a photoelectric effect is still possible.

Confirmation of these laws is the measurement of current and voltage. Based on the results obtained, it is possible to plot typical *current-voltage characteristics* (CVC) of the photoelectric effect (Fig. 5.6.1), that is, the dependence of the photocurrent over the voltage between the cathode and anode at constant illumination of the cathode E_1 and E_2 ($E_1 > E_2$).

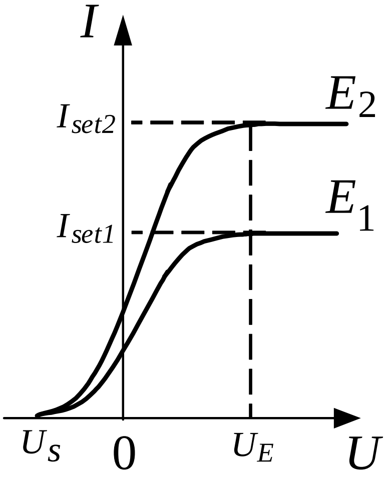


Fig. 5.6.1

From the graph $I = f(U)$ it can be seen that at some voltage $U_E > 0$ the photocurrent reaches its maximum value and then remains unchanged. This current, which is called *saturation current* I_s, corresponds to the state when all the photoelectrons that are pulled out by light from the cathode per unit time reach the anode, which confirms the first Stoletov's law.

From the CVC (Fig. 5.6.1) it can be seen that in the absence of voltage between the cathode and the anode, the photocurrent differs from zero. This is because some electrons that escape from the cathode under the action of light have kinetic energy sufficient to reach the anode regardless of the action of an external electric field. These electrons form a photocurrent at zero voltage (Fig. 5.6.1). In order to completely stop this current, between the cathode and the anode you need to create a field with a stopping voltage U_S, which completely slows down the electrons.

Then, as you know, the work of the electric field due to the deceleration of electrons will be equal to the change in their kinetic energy:

$$eU_S = \frac{m\upsilon_{max}^2}{2}, \qquad \text{(Eq. 5.6.2)}$$

where e – electron charge; $\upsilon_{\max}$ – maximum value of the speed of photoelectrons; m – mass of the electron; U_S – stopping voltage.

Write the equation (5.6.1) in the form:

$$eU_S = h\nu - \Phi,$$

hence:

$$U_S = \frac{h}{e}\nu - \frac{\Phi}{e}. \qquad \text{(Eq. 5.6.3)}$$

By measuring the braking voltage for the corresponding frequency of light, we can plot the dependence $U_S = f(\nu)$. This will be a straight line, from the equation of which one can determine the work function of electron of a given metal Φ and the value of the Planck constant h.

Having obtained the value of the electron work function from a given metal, we can calculate the red border of the photoelectric effect using the formula:

$$\lambda_r = \frac{hc}{\Phi}. \qquad \text{(Eq. 5.6.4)}$$

Pre-Laboratory Assignment

To perform the work, you need to study such a theoretical material: an external photoelectric effect and its laws; Einstein equation for an external photoelectric effect; photocells and their application.

The experimental equipment was assembled on the basis of a vacuum antimony-cesium photocell (Fig. 5.6.2). Cathode C is the inner surface of the glass cylinder B, covered with a photosensitive layer. The anode is a small disk A, located in the center of the cylinder.

The equipment diagram is shown in Fig. 5.6.2, where S – light source; F – photocell; L – variable light filter; P – potentiometer; G – galvanometer; V – voltmeter.

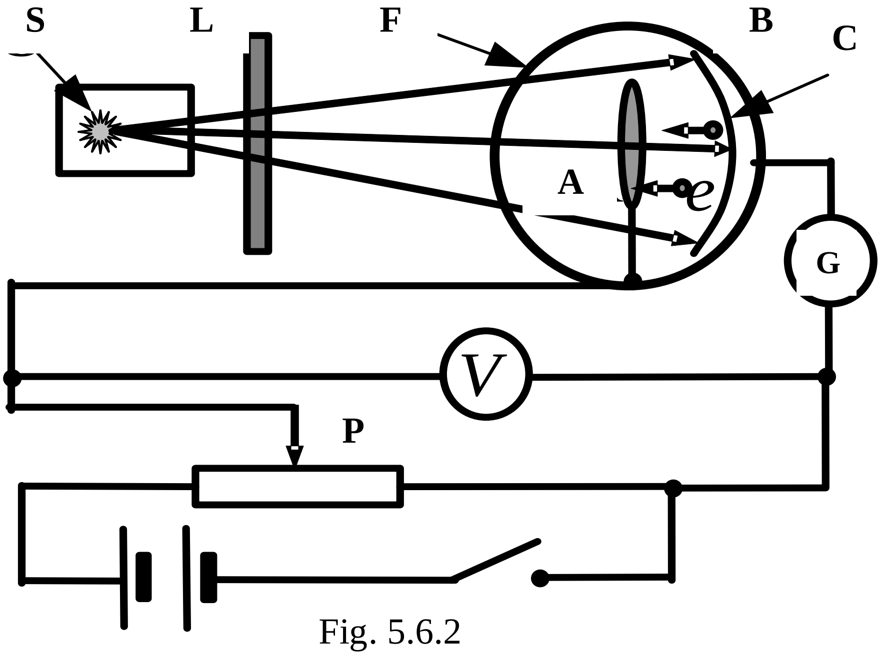


Fig. 5.6.2

Experimental Procedure

1. Write down in Table 5.6.1 frequency values of blue and orange light v (they are indicated on laboratory equipment).
2. Turn on the device and use potentiometer P to set the voltage between the cathode and anode to zero.
3. Turn on the light bulb, place a blue light filter in front of it. In this case, the galvanometer G must fix the value of the photocurrent other than zero.
4. Using a potentiometer, establish a negative voltage between the cathode and anode U_S at which there is no photocurrent in the circuit (I = 0).
5. Using a voltmeter, measure the value of the braking voltage U_S.
6. Perform operations 2-5 for the orange filter.

Calculations

1. Calculate the wave length λ for each of the filters in Excel.
2. Calculate the maximum photoelectron velocity υ_{max} for each of the cases (individual filters) by the equation (5.6.2) in Excel.
3. Plot a graph of the dependence $U_S = f(\nu)$ with the equation of the line (see Fig. 5.6.3) in Excel.
4. From the equation, determine the electron work function of a given metal (in eV) and the value of the Planck constant h. Calculate Φ in joules in Excel.
5. From the graph, determine the value of the minimum light frequency ν (min) and calculate in Excel the red border of the studied photosensitive layer of the photocell $\lambda_{r(1)}$ by the equation $\lambda_r = \dfrac{c}{\nu_{min}}$, where $c = 3 \cdot 10^8$ m/s.
6. Calculate the red border of the studied photosensitive layer of the photocell $\lambda_{r(2)}$ by the formula (5.6.4).
7. Calculate the average $\langle\lambda_r\rangle$.
8. Make all calculations in Excel and include them in Table 5.6.1.
9. Make a report in the form of Excel table and graphs.

Laboratory Report

Data and Calculations Table 5.6.1

	ν, Hz	c, m/s	λ, m	U_b, V	υ, m/s	W, eV	W, J	h, J·s	ν_{min}, Hz	$\lambda_{r(1)}$, m	$\lambda_{r(2)}$, m	$\langle\lambda_r\rangle$, m
Blue												
Orange												

Graphs

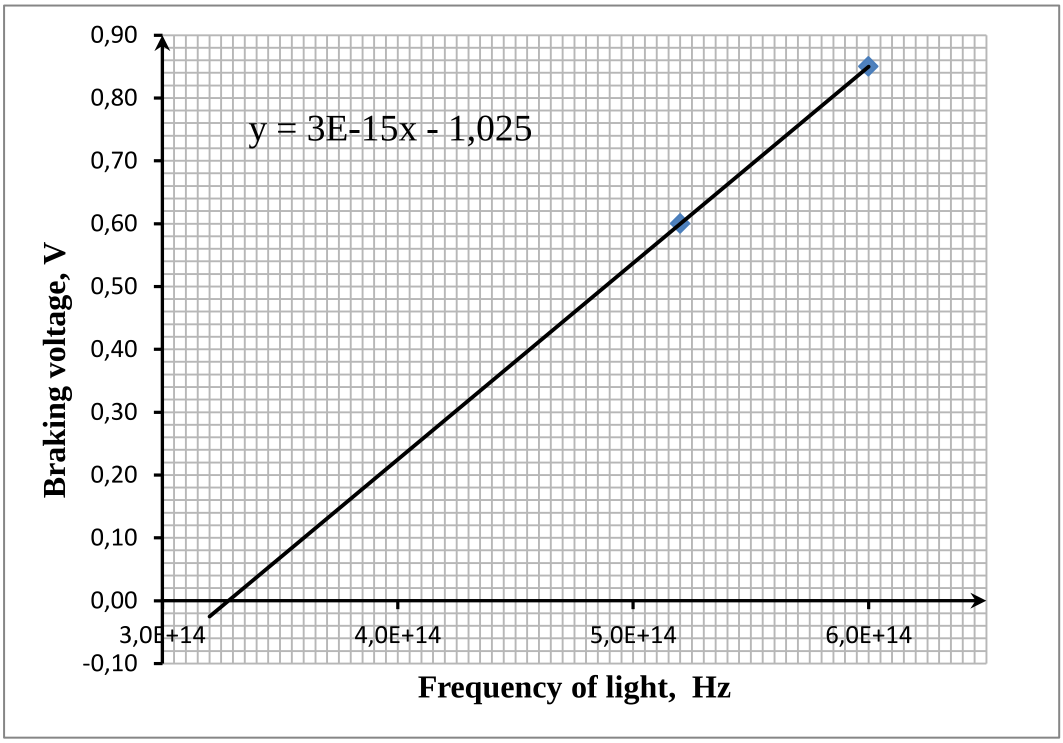


Fig. 5.6.3

Questions

1. What is the photoelectric effect? What is the difference between internal and external photoeffect?
2. Give an equipment diagram for studying the external photoelectric effect.
3. Show a typical current-voltage characteristic. What is saturation photocurrent and braking potential difference?
4. Formulate Stoletov's laws for the external photoelectric effect.
5. What is the red border of the photoelectric effect?
6. Record and explain the Einstein equation for the external photoelectric effect. What is a quantum of light (photon)?
7. What is the work function of electron of metal?
8. How to explain the laws of the photoelectric effect based on the Einstein equation?
9. Describe the photocells and their uses.

Laboratory 6.1

Determination of the Bandgap of a Semiconductor

Objective:

- Study the elements of the zone theory of solids.
- Determine the width of the bandgap semiconductor.

Equipment List

- Thermometer
- Oil bath
- Thermistor
- Heater
- Ohmmeter

Theory

To consideration the behavior of an electron in a solid, can apply the Schrodinger's equation and find possible states and values of its energy. This approach leads to the creation of *a zone theory of solids* based on an adiabatic approximation. Since the masses and velocities of nuclei and electrons differ significantly, we can assume that the nuclei in the nodes of the crystal lattice are not moving, so the motion of electrons is can considered in a constant periodic field of nuclei. Approximation of self-consistent field is also used.

Hence the interaction of certain electron with all other electrons is replaced by acting on it of a stationary periodic electric field, which is created by the averaged in a space charge of all other electrons and all nuclei.

Thus, in the zone theory of solids, it is multi-electron the problem is reduced to the problem of the motion of one electron in an external periodic field - *the averaged and self-consistent field of all nuclei and electrons*.

Consider the formation of solids from isolated atoms. The electrons of a single, isolated atom occupy atomic orbitals each of which has a discrete energy level. When two or more atoms join together to form into a molecule, their atomic orbitals overlap.

The Pauli exclusion principle dictates that no two electrons can have the same quantum numbers in a molecule. So if two identical atoms combine to form a diatomic molecule, each atomic orbital splits into two molecular orbitals of different energy, allowing the electrons in the former atomic orbitals to occupy the new orbital structure without any having the same energy (see Fig. 6.1.1).

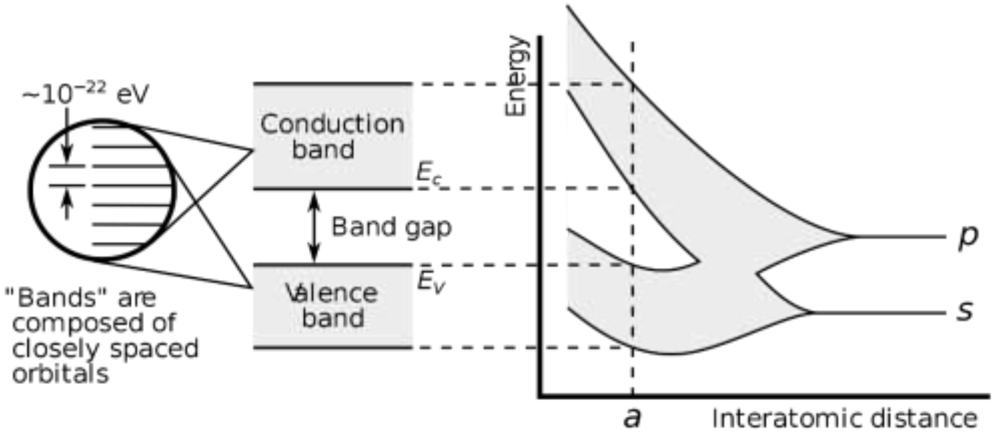


Fig. 6.1.1

Similarly, if a large number N of identical atoms come together to form a solid, such as a crystal lattice, the atoms' atomic orbitals overlap. Since the Pauli exclusion principle dictates that no two electrons in the solid have the same quantum numbers, each atomic orbital split into N discrete molecular orbitals, each with a different energy.

Since the number of atoms in a macroscopic piece of solid is a very large number ($N \sim 10^{22}$) the number of orbitals is very large and thus they are very closely spaced in energy (of the order of 10^{-22} eV). The energy of adjacent levels is so close together that they can be considered as a continuum, an energy band so-called *band energy spectrum* (Fig. 6.1.1).

This formation of bands is mostly a feature of the outermost electrons (valence electrons) in the atom, which are the ones involved in chemical bonding and electrical conductivity. The inner electron orbitals do not overlap to a significant degree, so their bands are very narrow. The formation of a *band energy spectrum* in a crystal is a quantum mechanical phenomenon and follows from the Heisenberg's uncertainty principle and the Pauli's principle.

In a crystal, the valence electrons of atoms can move from atom to atom through potential barriers separating atoms, that is, to move without changing the total energy (tunnel effect). This leads to the fact that the average lifetime of a valence electron in this atom is significantly reduced compared to an isolated atom and is approximately 10^{-15} s (for an isolated atom it is about 10^{-8} s). The lifetime of an electron in any state is associated with the uncertainty of its energy (width of the level) by the uncertainty relation $\Delta W \cdot \tau \geq \hbar$.

Therefore, if the natural width of the spectral line of individual atoms is approximately 10^{-7} eV, then in crystals it reaches 1 eV - 10 eV, which is, the energy levels of the valence electrons extend into the allowed energy range.

The energy of external electrons can take values within the limits of the painted areas that are called permitted energy zones. Each allowed zone "holds" as close to the discrete levels as the atoms contained in the crystal.

Allowable energy zones are separated by zones of forbidden values of energy, which are called forbidden energy zones. The distance between adjacent levels in the zone is approximately 10^{-22}eV. Since this is a very small value, the zones can be regarded as practically continuous, but the fact of a finite number of levels in the zone plays an important role in the distribution of electrons in the energy states. In the forbidden zone the electrons cannot be located, that is, the electron cannot have the corresponding energy value. The width of the zones (allowed and forbidden) does not depend on the size of the crystal. Allowed zones are wider, the weaker the bond between the electron and the nucleus.

Zone theory of solids explains the separation of solids into metals, dielectrics and semiconductors, given the difference in their electrical conductivity. First, the different filling of the allowed zones by electrons and, second, the different value of the band gap.

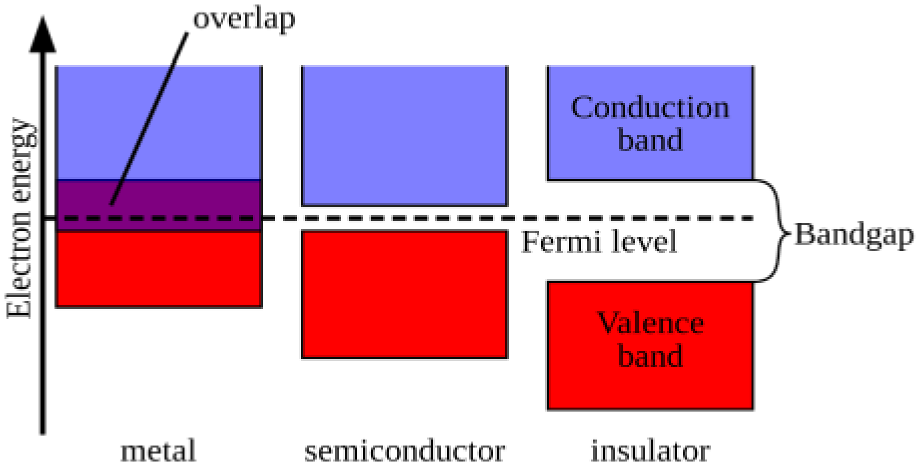
The degree of electron filling in the energy levels in the zone is determined by filling the corresponding atomic level. If, for example, a certain atomic level is completely filled with electrons in accordance with the Pauli principle, then the zone formed by it is also completely filled.

In the general case we can speak of a *valence band* which is completely filled with electrons and formed from the energy levels of the internal electrons of free atoms, and about the *conduction band* (free zone), which is either partially filled with electrons or free electrons, and formed from the energy levels of the outer "collectivized" electrons isolated atoms (Fig. 6.1.1).

Depending on the filling of the zones by the electrons and the width of the gap, there may be four cases, three of which shown in Fig. 6.1.2.

If the conduction band is only partially filled with electrons, ie there are free levels in it, then the electron, having received little energy (eg through thermal excitation or an electric field), can move to a higher energy level, ie become free and participate in the conduction process. Thus, the concentration of free electrons in the conduction band increases and the body will conduct an electric current. This is what is characteristic of metals.

Solids will be conductors of electric current also if the valence band is covered by a free zone, which leads to a partially filled zone (Fig. 6.1.2, a). In this case, a so-called "hybrid" zone is formed, which is only partially filled by valence electrons.



a b c

Fig. 6.1.2

This is the case for alkaline earth elements (Be, Mg, Ca, Zn, etc.). Solids in which the energy spectrum of the electronic states consists of a filled (or partially filled) valence band and a free conduction band, depending on the gap width of the band ΔW, will be dielectrics or semiconductors.

If the gap width of the crystal ΔW is sufficiently large (several electron volts), then thermal energy is not sufficient to transfer electrons from the valence band to the conduction band, and the crystal will be a dielectric (Fig. 6.1.2, c).

If the width of the band gap ΔW is not large (about 1 eV), then the transition of the electron from the valence band to the conduction band can be made relatively easily either by thermal excitation or by external a source that is able to give the electrons energy not less than the width of the band gap and the crystal will be a semiconductor (Fig. 6.1.2, b).

The main one difference between metals and dielectrics from the point of view of the zone theory is that at T = 0 K there are electrons in the conduction band of metals, and they are absent in the conduction band of dielectrics.

The difference between dielectrics and semiconductors is determined by the width of the forbidden zone: for dielectrics it is several electron volts, for semiconductors – about 1 eV. At temperatures close to 0 K, semiconductors behave like insulators. As the temperature increases in semiconductors, the number of electrons increases, which, as a result of thermal excitation, pass into conduction band, hence the electrical conductivity of semiconductors in this case increases.

In nature, semiconductors exist in the form of elements of the IV, V and VI groups of the periodic system of elements, such as Si, Ge, As, Se, Te, as well as chemical compounds, such as oxides, sulfides, selenides, and alloys of elements of various groups.

Distinguish *Pure* and *Admixture* semiconductors. An example of pure semiconductors can be chemically pure substances Ge, Se, as well as many chemical compounds: InSb, GaAs, CdS, etc.

A $T = 0$ K pure semiconductors behave like dielectrics. At increases temperatures, electrons from the upper levels of the valence band can be thrown over to the lower levels of the conduction band. When applied to a crystal of an electric field, they move against the field and create an electric current.

In solid-state physics it is proved that the specific conductivity of a pure semiconductor depends on the temperature according to the exponential law:

$$\gamma = A \cdot \exp\left(-\frac{\Delta W}{2kT}\right),$$

where A – proportionality factor; ΔW - bandgap width; k – Boltzmann's constant; T – absolute temperature.

Taking into account the inverse relationship between resistivity and conductivity $(\gamma = {}^{1}\!/\!_{\rho})$, and the linear relationship between resistance R and resistivity, one can determine the resistance of the semiconductor by the equation:

$$R = A \cdot \exp {}^{\Delta W}\!/\!_{2kT}. \qquad \text{(Eq. 6.1.1)}$$

The coefficient A also depends on the temperature, but compared with the exponential component, this dependence is very weak, so coefficient A can be considered constant in a narrow range of temperatures.

Logarithm equation 6.1.1:

$$\ln R = \ln A + \frac{\Delta W}{2k}\left(\frac{1}{T}\right). \qquad \text{(Eq. 6.1.2)}$$

The graph of dependence $\ln R = f\left({}^{1}\!/\!_{T}\right)\cdot$ will be a straight line, the gradient of which is:

$$\text{grad} = \frac{\Delta W}{2k}. \qquad \text{(Eq. 6.1.3)}$$

Since the values of the bandgap is:

$$\Delta W = \text{grad} \times 2k. \qquad \text{(Eq. 6.1.4)}$$

Figure 6.1.3 shows the scheme of the experimental installation. Where 1 – thermometer; 2 – oil bath; 3 – thermistor; 4 – heater; 5 – ohmmeter.

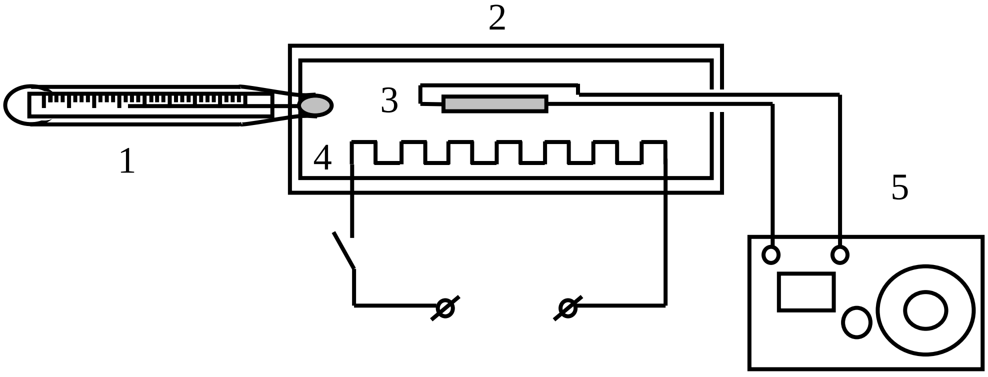


Fig. 6.1.3

Pre-Laboratory Assignment

To perform the work, you need to study such a theoretical material: the splitting of energy levels and the emergence of energy zones in crystals; Pauli's principle; distribution of electrons in energy states; the division of solids into conductors, semiconductors and dielectrics in terms of band theory.

Experimental Procedure

1. Using an ohmmeter, determine the resistance of the thermistor at room temperature.
2. Turn on the heater and measure the resistance with an ohmmeter every 5 ^{o}C. The temperature should not exceed 80 ºC.
3. Write the results of measurements in Table 6.1.1.

Calculations

1. Construct a ln$R$ dependency graph from 1/T using the Excel with equation this function (see Fig. 6.1.4).
2. From the equation, determine the gradient and calculate the bandgap from the relation (6.1.3) in Excel.
3. Calculate the width of the bandgap by formula (6.1.4).
4. To express the values of the bandgap width in electron volts, taking into account that 1 eV = 1.6 10^{-19}J.
5. Make a report in the form of Excel table and graphs.

Laboratory Report

Data and Calculations Table 6.1.1

t, ^{o}C	T, K	$\frac{1}{T}$, K^{-1}	R, Ω	ln$R$	*grad*	ΔW, J	ΔW, eV

Graph

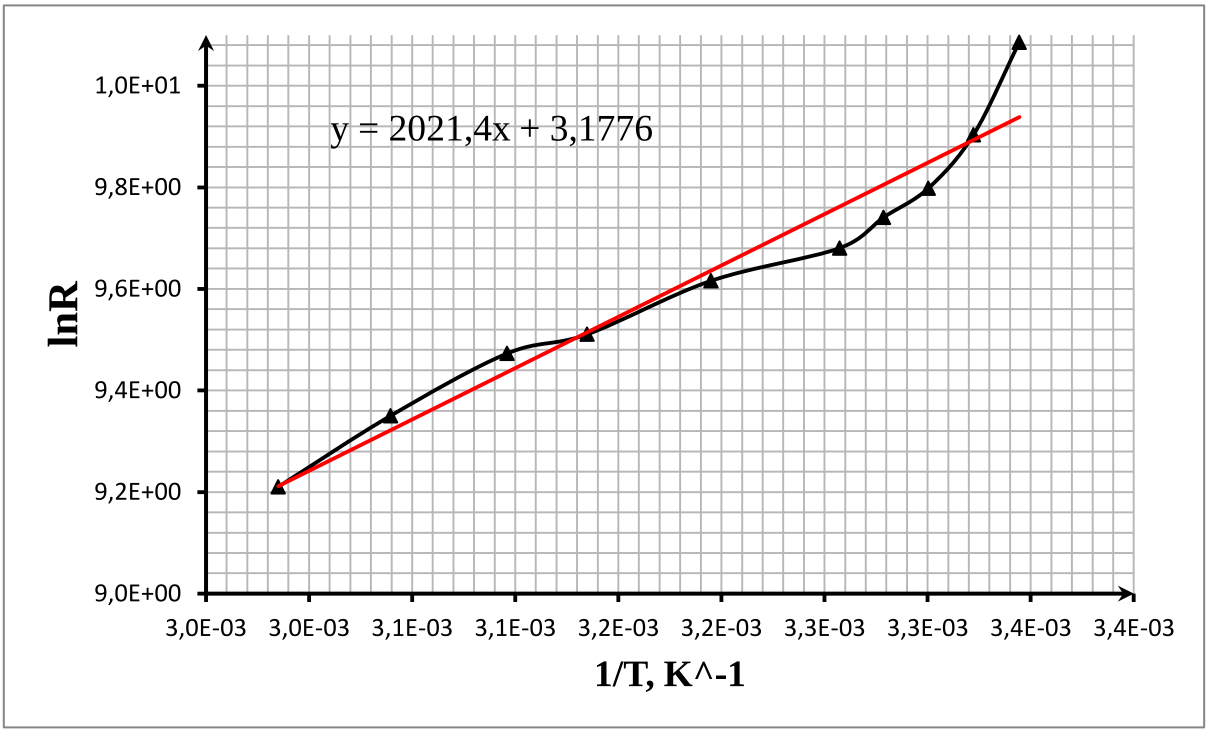


Fig. 6.1.4

Questions

1. Explain the reason for the splitting of energy levels and the emergence of energy zones in crystals from the point of view of solid zone theory.
2. Formulate Pauli's principle.
3. What are the conductors, semiconductors and dielectrics in terms of solid-state theory?
4. What is valence zone? What is the conduction band?
5. Explain what is the forbidden zone?
6. What is Fermi's level?
7. According to what principle are filled zones in the crystal?
8. What elements of the group of the Mendeleev table relate mainly to semiconductors?
9. What is the dependence of semiconductor resistance on temperature? Explain the reason for this dependency.
10. Is it possible to make dielectric a conductor? How?

Laboratory 6.2

Measurement of Current-Voltage Characteristic of Semiconductor Diode

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Objectives:

- Investigate possibilities of p-n junction and its rectifier action.
- Measure current-voltage characteristic of semiconductor diode.

Equipment List

- Semiconductor diode
- Ampermmeter
- Voltmetter
- Switch

Theory

Semiconductor diode – type of diode, which contains “p-n junction” made from differently doped semiconductor materials. It is double-ended, nonlinear electronic component, where terminal attached to the “p” layer (+) is called anode and “n” layer (–) cathode. This electronic component is mainly used because of its ability of making electric current flow only in one direction (from anode to cathode) after forward-biasing the aforementioned “p-n junction” with the positive electric voltage.

However, in the opposite direction (reverse bias of the “p-n” junction with the negative electric voltage) we can say that in ideal semiconductor diode electric current will not flow. This is why semiconductor diode is often described as the “electric valve”, which can pass or block the flow of the electric current.

A staple of semiconductor rectifiers is semiconductor (crystalline) diodes that have some payments was comparable with vacuum diodes. Namely its small size, high mechanical durability, long lifetime and other positive specifics of semiconductors diodes.

In the basic of work semiconductor diodes is rectifier action of p-n junction (electronic-hole junction). P-n junction is a thin layer between two areas of semiconductor, which vary by type of conduction. Semiconductors have two different types of conductance: electric and hole conductance.

The electron hole is a vacancy created by the electron “travelling” from its initial place to some other location in that crystal. In reality, there is no such thing as “a hole”, but that lack of electron kind of makes it a positively charged particle, which attracts negative electrons to form a pair again (holes can move too).

To do admixture semiconductor with electronic type of conduction (n-type semiconductor) in crystal of germanium or silicon (4-valence substance) add admixture atoms with bigger valence, for example, 5-valence Arsenic. Therefore, to create covalent bonds with atoms of main substance of arsenic it is enough 4 electrons. Fifth electron, which is not linked to a lattice, after giving him insignificant amount of energy ΔW_1 (Fig. 6.2.1, a) becomes free and it is called *conduction electron*.

Admixture atoms(arseniac) becomes positive ion, which can’t move in crystal. Admixtures that supply the conduction electrons are called *donors*. Admixtures distort electric field of lattice, which leads to appearance of local energetic levels. These levels are accommodated in the restricted zone of crystal (Fig. 6.2.1). Fermi’s level in n – is a type semiconductor between a donorlevel and bottom of conduction zone.

To create admixture semiconductor with hole conduction (p-type semiconductor) in germanium or silicon crystal add admixture atoms with smaller valence, for example, boron, which has three valence electrons. Three valence electrons of boron atom are not enough to make double covalent bound with four nearby atoms of main substance. Therefore, boron atom captures one from valence electron of germanium (or silicon) and becomes negative charge ion. In place of captured electron stays hole – quasi particle, which has positive charge which equals electron's charge. After giving hole insignificant amount of energy ΔW_2 (Fig. 6.2.1, b), it becomes free charge carrier.

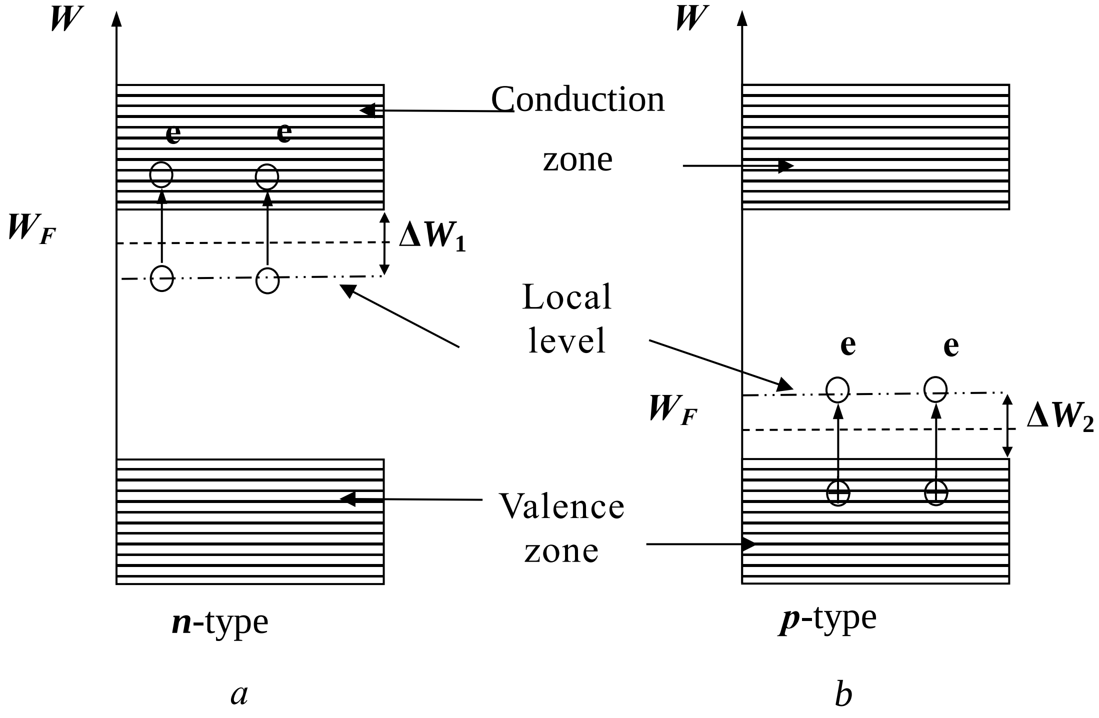

Fig. 6.2.1

Admixture atoms, which can capture electrons from valence zone, called *acceptors*. Acceptor energy levels placed little higher than crystal valence zone top edge (Fig. 6.2.1, b). Fermi level in p-type semiconductors lies between top level of valence zone and acceptor level (Fig. 6.2.1, b).

So, if concentration of free electrons in semiconductor higher then concentration of holes, than this semiconductor has electronic conductance and called *n-type semiconductor*. If exceeds concentration of holes, then semiconductor have hole conduction and called *p-type semiconductor*.

Let’s look on the process on the boundary of two semiconductors with different type of conduction (Fig. 6.2.2). Since of concentration of free electrons in n- region is bigger, than in p-region, electrons diffusing through contact to the side of p- region. In the opposite direction moving holes. Reaching areas with opposite conduction, electrons recombine with holes, therefore near the boundary decreasing concentration of free electrons and holes.

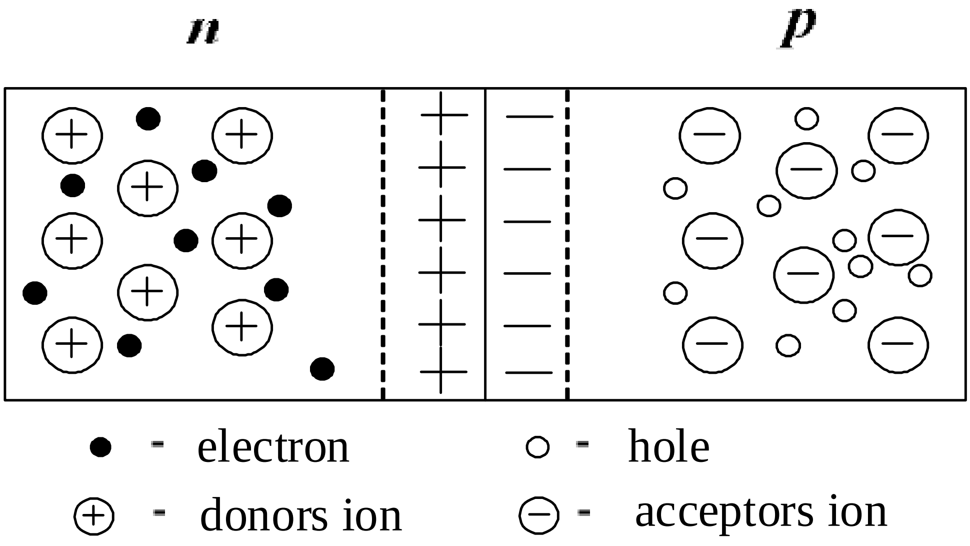

Fig. 6.2.2

Since the atomic residues in the n-region have a positive charge, and in the p-region, they have a negative charge, therefore, a positive charge is accumulated in the n-region near the edge, and a negative charge is accumulated near the p-region. Such a forming called *p-n junction*. It leads to appearance of Volta potential (Rectangular potential barrier) between p-type and n-type semiconductors, which block moving through limit of main charge carriers: electrons from n-region and holes from p-region.

In the same time, electrical field, which formed on p-n junction, stimulate movement of not basic current carriers through p-n junction. In the absences of external electric field full electric current through p-n junction is equal to zero due to dynamic equilibrium which is installed on boundary, when average number of charges, which moves in opposite direction to electric field, balanced by charges, which pass through boundary in opposite direction.

By experimental way found out: in some cases, contact of two semiconductors has property to conduct electric current mainly in one direction.

Now will connect semiconductor diode to electric field that exterior potential different reduced contact potential (*direct direction*, Fig. 6.2.3, b). In this case decreases height of Rectangular potential barrier for main charge.

External electric field "to press" main carriers of current to the boundary. Because of this reason, width of p-n junction reduces. Accordingly reduced resistance of p-n junction and the greater the greater the external voltage. Trough p-n junction comes electric current, conditioned to main charge carriers, value of which with increase of voltage grows by exponential law.

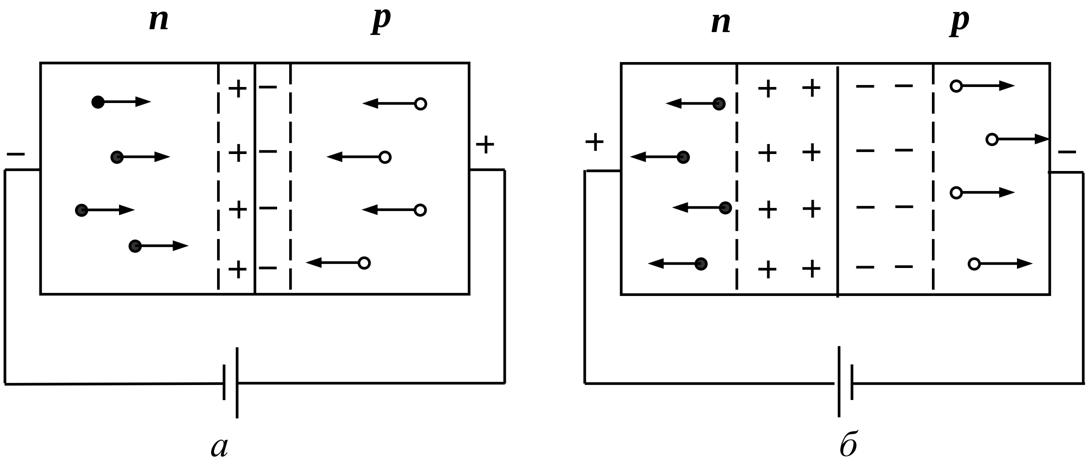

Fig. 6.2.3

Polarity change of external battery (reverse direction) leads to increase in height of Rectangular potential barrier for main charge carries (Fig. 6.2.3, a). External electric field "puls out" main charges from the boundary, resulting increment of width of p-n junction and its resistance. Main carriers cannot overcome rectangular potential barrier meanwhile flow of not basic charge carriers does not change (there in no barrier to them). Through p-n junction moving small current I (saturation current), which value has little depended from voltage. Therefore, p-n junction has property of one-way conductivity, and can be used to rectify alternating current.

Dependency of value of current from applied voltage $I = f(U)$ in direct and reverse direction through p-n junction is called characteristic of Current-Voltage CVC (Fig. 6.2.4).

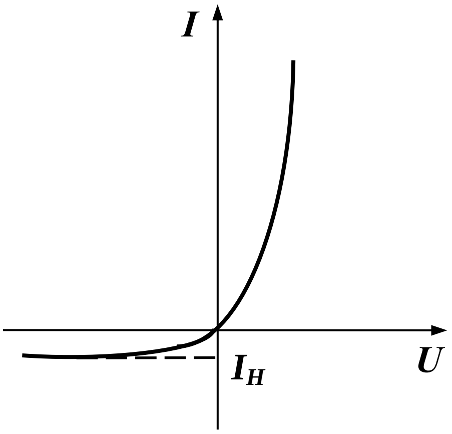

Fig. 6.2.4

To research unilateral conductivity of p-n junction, in this work we will use semiconductor photodiode. Since of current in direct direction much bigger than in reversed direction, to measure them use instruments of diferent sensivity. Current in reversed direction measure by microampermmeter, current in direct direction - by miliampermmeter. On the panel of laboratory work there is a switch, which gives us possibility switches diod in direct and reversed directions.

Pre-Laboratory Assignment

To perform the work, you need to study such a theoretical material: pure and impurity conductivity of semiconductors; p-type and n-type semiconductors; pin difference of potentials; contact of p-type and n-type semiconductors (p-n junction). Please read the instructions from Laboratory 6.1 before performing the work.

Experimental Procedure

1. Acquaint of electrical diagram.
2. Measure voltage for current diferent values (write down CVC) for direct direction of current.
3. Change current direction through diod via the switch. Measure CVC in reverse current mode.
4. Write in Excel Table 6.2.1 results of mesurment.

Calculations

1. Build a graphs dependend current from voltage (CVC) for direct and reverse mode of work of semiconductor diod in Excel.
2. For linear section CVC set a straight line equation (grad) in Excel (Fig. 6.2.5, example) and by gradient determine internal resistance semiconductor diod in direct and reverse modes of his work:

$$R=1/(\text{grad}).$$

3. Make a report in the form of Excel table 6.3.1 and graphs.

Graph

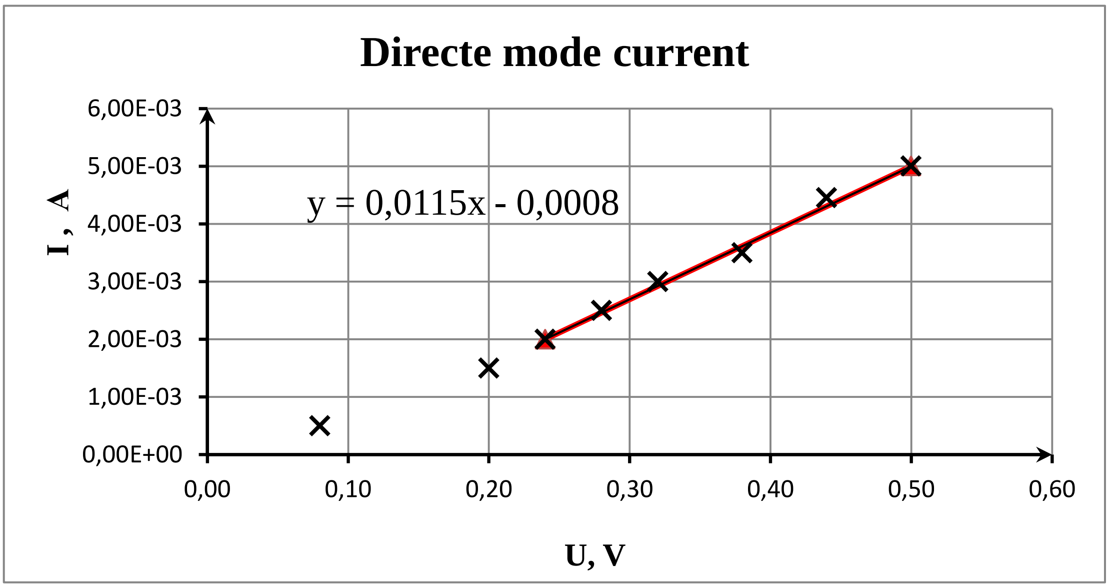

Fig. 6.2.5

Laboratory Report

Data and Calculations Table 6.3.1

Directe mode current			Reverse mode current		
U, V	$I \cdot 10^{-3}$, A	R, Ω	U, V	$I \cdot 10^{-6}$, A	R, Ω

Questions

1. What is called impurity conductance?
2. What is n-type semiconductor? Which charge carriers is main in n-type semiconductors?
3. Draw n-type semiconductor zone diagram. Where is located Fermi's level in impurity n-type semiconductor?
4. What is p-type semiconductor? Which charge carriers is main in p-type semiconductors?
5. Draw p-type semiconductor zone diagram. Where located Fermi's level in impurity p-type semiconductor?
6. What is n-p junction and how technicly get it?
7. How arise contact electric field and Rectangular potential barrier for charge carriers in n-p junction?
8. Why locking layer of n-p junction has big resistance?
9. Draw CVC for n-p junction, explain look of separates zones.
10. What advantages have crystalline diodes against LED diodes?

Laboratory 6.3

Measurement of Light Characteristics of Valve Photodiode

Objectives:

- Investigate the phenomenon of photo-EMF occurrence in photocells with lock layer.
- Determine the luminous characteristic of the valve photocell and its integral sensitivity.

Equipment List

- Light source
- Photocell
- Battery
- Ruler
- Ammeter

Theory

The *photovoltaic effect* is the creation of voltage and electric current in a material upon exposure to light. It is a physical and chemical phenomenon. This phenomenon used in devices, which call photodiodes**.**

Photodiode is a type of semiconductor diode that serves as a detector of light. Its electrical properties are dependent on the light radiation that is illuminating it. It is easy to recognize this component among other semiconductor diodes due to its characteristic housing with transparent window. Internal photodiode component construction is based on the p-n junction or p-i-n structure (p-i-n-with an intrinsic or undoped layer between two p-n doped semiconductor crystals).

Valve photoelectric cell based on silicon, germanium and sulfur silver etc. widely used in science and technique for direct conversion of light energy in electric current energy and registration and measurement of light flux. Silicon and some other valve photoelectric cells used for production of “Sun” cells, for example for power supply of radio equipment of artificial earth satellite. Their energy conversion efficiency is 10 - 11 %.

Valve photoelectric cell consists of metal plate 1, surface of which covered by crystalline n-type semiconductor 2 (Fig. 6.3.1) with translucent protective layer (3) from the same metal. Between metal layers (1) and semiconductor n-type (2) forms M-m contact (metal-semiconductor) with locking layer.

The same lock layer appears on contact of semiconductor n-type (2) with metal coating (3). In this case, the contact potential differences are the same and included in the circle to meet. The equivalent circuit of the valve photocell is show in Figure 6.3.2.

The emergence of an EMF on a photoelectric element is caused by the phenomenon of an internal photoelectric effect in the interlocking layer *K*2 due to the light entering it through a transparent metal coating 3.

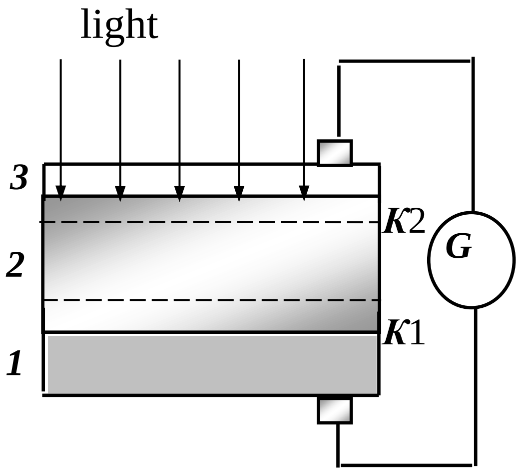

Fig. 6.3.1

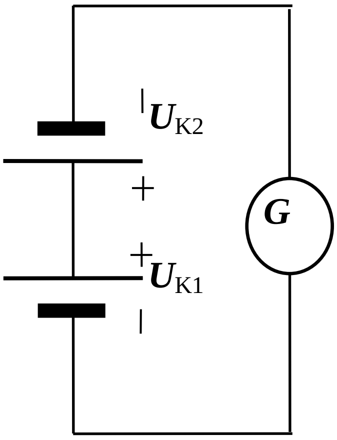

Fig. 6.3.2

In the absence of irradiation, the contact potential differences of $U_{\mathrm{K}1}$ and $U_{\mathrm{K}2}$ are the same in magnitude. They are included in the circle to meet (see Fig. 6.3.2), the potential difference is

$$\varepsilon = U_{\mathrm{K}1} - U_{\mathrm{K}2}. \qquad \text{(Eq. 6.3.1)}$$

This is potential difference is zero and no current passes through the galvanometer because of in circle (Figure 6.3.2) they are included toward each other.

In the presence of a luminous flux, additional charge carriers (photoelectrons and photo holes) appear in the $K2$ interlayer, reducing the contact potential difference of $U_{\mathrm{K}2}$ so that the photo-EMF according to (Eq. 6.3.1) becomes non-zero. This decrease occurs at the contact $K2$, whose energy band structure is show in Figure 6.3.3.

Locking layer Δx (Fig. 6.3.3) for contact metal-n-type semiconductor is formed when work function (which gives the minimum energy required to remove an electron from the surface of the metal) for metal Φ_M is bigger than work function to exit from n-type semiconductor Φn. Thus arises equilibrium external potential difference $U_{\mathrm{K}2}$:

$$U_{\mathrm{K}2} = \frac{\Phi_M - \Phi_n}{e}.$$

This means metal has redundant negative charge, n-type semiconductor-positive, appears contact electric field, electric field vector $\vec{E}_\kappa$ showed on Figure 6.3.3.

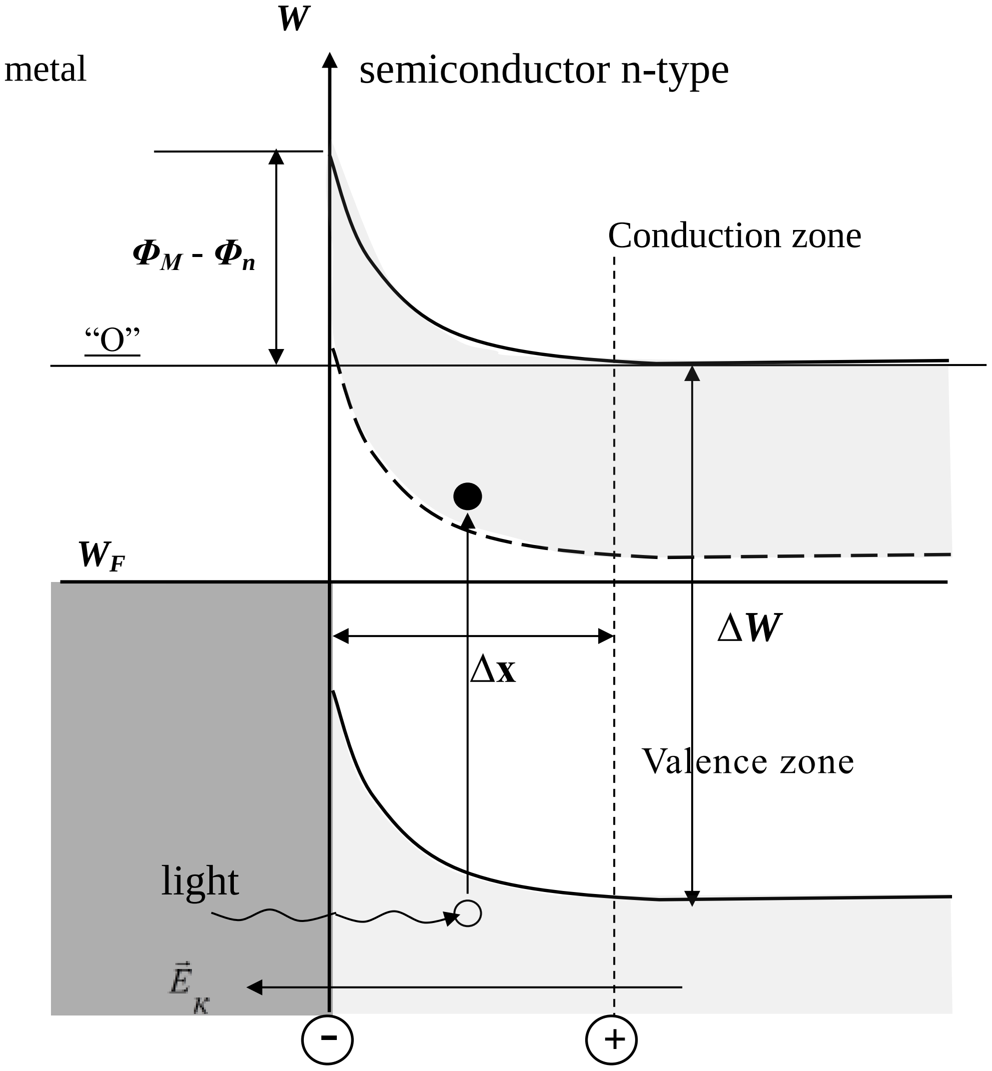

Fig. 6.3.3

Photon pictured by wavy line with arrow (Fig. 6.3.3) gets in locking layer through translucent metal and cause inner photo effect. So, electron is going from valence zone (VZ) to conduction zone (CZ). This leads to appearance of two extra charge carriers: hole in VZ and electron in CZ. Under the action of electric field electron goes to semiconductor zone, and hole goes accordingly to metal zone. This compensates for the excess charges that have arisen during the metal-semiconductor contact, and with it the contact potential difference U_{K2}.

The continuous flow of such quanta causes a constant decrease of this contact potential difference so that the photo-EMF (Eq. 6.3.1) will be non-zero and therefore non-zero will be the current in the circuit.

The light characteristic of the photocell is called the dependence of the photocurrent I on the luminous flux incident on it I = f (Φ). One of the characteristics of a photocell is integral sensitivity. It is numerically equal to the increase in photocurrent in the case of growth per unit the luminous flux:

$$q_i = \frac{dI}{d\Phi}. \qquad \text{(Eq. 6.3.2)}$$

The integral sensitivity can be obtained from the graph of the dependence of photocurrent and luminous flux, that is, the gradient of the linear part of this graph and will be this value.

Given that the luminous intensity of the lamp j remains constant, the luminous flux Φ incident on the surface of the photocell by area S is calculated by the known equation:

$$\Phi = j\frac{S\cos\alpha}{r^2}, \qquad \text{(Eq. 6.3.3)}$$

where Φ – luminous flux; j – luminosity intensity of the light source; S – surface area of the photocell; α – angle that makes normal to surface of photocell with the direction of the luminous flux; r – distance between photocell and light source.

The diagram of this investigation is shown in Figure 6.3.4. To determine the luminous flux Φ incident on the surface of the photocell *2*, it is necessary changing the distance r from the photocell to the light source *1*.

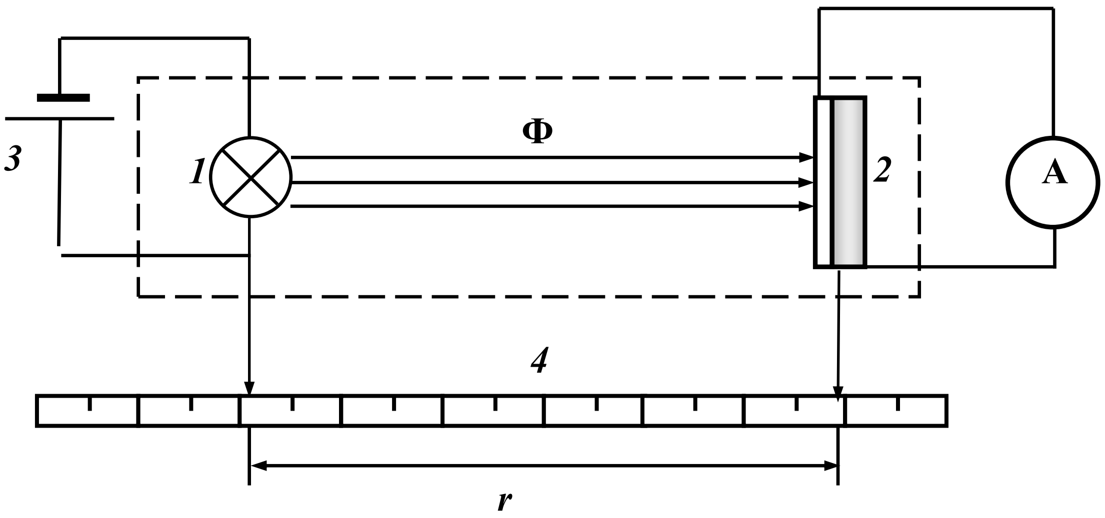

Fig. 6.3.4

Pre-Laboratory assignment

To perform the work, you need to study such a theoretical material: pure and impurity conductance of semiconductors; p-type and n-type semiconductors; contact of p-type and n-type semiconductors (p-n junction); contacts M-n and M-p; contact potential difference; photovoltaic effect in semiconductor and their practical usage. Before completing work read instructions for *Laboratory* 6.1, 6.2.

Experimental Procedure

1. Set the photocell so that the angle $\alpha = 0^{o}$.

2. Turn on the light source.

3. Changing the distance r from the light source to the photocell (5 – 7 values), record the microammeter I.

4. Repeat step 3 for angle $\alpha = 60^{o}$.

5. The measurement results are recorded in Table 6.3.1 in Excel.

6. Record the values of the luminosity intensity of the light source *j* and the surface area of the photocell *S* (indicated in the installation) in Table 6.3.1

Calculation

1. Calculate in Excel luminous flux Φ for every *r* meaning using Equation 6.3.3.
2. Build light characteristic of photocell I =f (Φ) in Excel.
3. To build straight line on the linear part of the graph I =f (Φ).
4. Write down equations of this straight line.
5. Determine integral sensitivity q_i photocell from this equation.
6. All calculations make in Excel and write in Table 6.3.1.
7. Make a report in the form of Excel table and graphs.

Laboratory Report

Data and Calculations Table 6.3.1

r, m	I, A	j, cd	S, m^2	Φ, lm	q_i, A/lm

Questions

1. What is called the pure and impurity conductivity of semiconductors?
2. What is the internal photo effect?
3. What is called the "red border" of internal photoelectric effect?
4. Show schematically the structure of the valve photocell and explain how it works.
5. How does a direct conversion of light energy into electrical energy occur in a valve cell?

6. What is the spectral sensitivity of a photocell?
7. Give examples of using photocells.
8. What causes the low efficiency of photovoltaic cells?

Laboratory 7.1

Determination of radioactive source activity

Objective:

- Getting acquainted with different types of radioactive radiation and methods of their registration.
- Determination of radioactive source activity using a Geiger counter.

Equipment List

- Radioactive source
- Geiger counter
- Ruler
- high-voltage rectifier
- Stopwatch
- Impulse counter
- Obstacle

Theory

The atomic nucleus is the central part of the atom, in which the positive charge and almost all its mass are concentrated. It consists of nucleons (positively charged protons ${}_{1}^{1}p$ and neutral neutrons ${}_{0}^{1}n$) held together by nuclear forces. The number of protons in the nucleus is called the charge number *Z*, which is equal to the ordinal number of the element in the Periodic table. The number of neutrons in the nucleus is called the isotonic number *N*. The sum of the numbers $Z + N$ shows the total number of nucleons of the nucleus A and about the average mass of the atom. The nucleus is denoted as ${}_Z^A X$. Nuclei with the same number Z and different N are called – isotopes, with the same number of N and different Z – isotons, with the same A but different Z and N – isobars.

It is known that unstable nuclei, as well as all nuclei in the excited state, transform spontaneously, which leads to changes in the composition of the nucleus and its internal energy. Such spontaneous processes of nuclear transformations are called *radioactivity*.

The law under which radioactive decay of nuclei occurs binds the initial number of nuclei (N_0), which decay, with the number of nuclei not decaying in a certain amount of time (t):

$$N = N_0 e^{-\lambda t}, \qquad \text{(Eq. 7.1.1)}$$

where λ – decay constant which can be expressed through the half-life.

Decay constant and time at which half of the original nuclei will disintegrate $T_{1/2}$ are related by the ratio:

$$\lambda = \ln 2 / T_{1/2}.$$

However, such a law is valid only if the subsidiaries nuclei are stable.

In other cases, further decay of the formed nuclei will be observed for which the decay constant is different. Such a decay sequence is described by systems of differential equations:

$$\frac{dN_1}{dt} = -\lambda_1 N_1, \qquad \frac{dN_2}{dt} = -\lambda_2 N_2 + \lambda_1 N_1.$$

If the $T_{1/2}$ native nucleus $>> T_{1/2}$ subsidiaries isotope, then $\lambda_1 N_1 \approx \lambda_2 N_2$.

The main types of radioactive transformations are α-, β^+-, β^-- decays, γ - radiation, *e* – absorption spontaneous fission, proton radioactivity.

Consider some basic types of radioactive transformations.

1. *α-particle radiation*. The decay of the nucleus occurs with the departure of the nucleus of the atom ^4_2He. The decay of the nucleus occurs with the departure of the nucleus of the atom. The Soddy displacement rule, which allows to determine the location of the isotope - decay product in the periodic system of elements, can be written for alpha decay as follows:

$$^A_ZX \rightarrow {}^{A\text{-}4}_{Z\text{-}2}Y + {}^4_2He.$$

In order for alpha decay to occur, the binding energy of the subsidiary's nucleus and α-particles must be separately greater than that of the native nucleus, which means that energy is released in the process. The α-particle has a charge, so in order to leave the nucleus, it must overcome the Coulomb barrier. As a result, α -decay occurs overtime $10^{-10} \div 10^{-7}$s.

2. *β-particle radiation.* The nucleus emits an electron/positron**.** The process occurs only inside the nucleus, when one of the neutrons (protons) breaks down, forming a proton and an electron (neutron and positron).

$$n \rightarrow p + e^- + \tilde{\nu}_e, \qquad p \rightarrow n + e^+ + \nu_e\ ,$$

where $\tilde{\nu}_e$, ν_e – electronic antineutrinos and neutrinos emitted during the β-decay process.

The existence of these particles was predicted theoretically to substantiate the energy spectrum of β-particles. The neutrino/antineutrino has zero charge and rest mass and spin $\hbar/2$.

The free neutron can decay ($T_{1/2} \approx$ 11-15 min) beyond the nucleus, and may remain stable in the nucleus. A proton, by contrast, is considered to be a stable particle ($T_{1/2} \approx$ 1029 years) outside the nucleus and can decay into a neutron inside.

3. *γ-radiation* is high-permeability electromagnetic waves that are not deflected in either electric or magnetic fields. It does not occur independently, but accompanies α-, β- decays, occurs in

nuclear reactions, in the processes of inhibition of charged particles, in the process of their decay. The γ spectrum has a linear structure. This type of radioactive radiation is not described by the displacement rule because A and Z nuclei remain unchanged in these processes.

The main mechanisms of interaction of γ-radiation with a matter, which lead to a decrease in its intensity, are photoeffect, Compton Effect and the birth of electron-positron pairs.

An important characteristic of a radioactive source is its activity (A), which shows many nuclei (dN) of the corresponding isotope decays per unit time:

$$A = \left| \frac{dN}{dt} \right| = \lambda N . \qquad \text{(Eq. 7.1.2)}$$

Units of radioactivity [1 Ki] = [$3.7 \cdot 10^{10}$Bq].

The transformation of the nucleus is always accompanied by the emission of γ-quanta, so the activity of source can be estimated by the number of γ-quanta emitted by the source per unit time and recorded by the counter. To determine the number of nuclei (N) in the mass of matter (m), can use the mole:

$$\nu = \frac{N}{N_A} = \frac{m}{\mu}, \qquad \text{(Eq. 7.1.3)}$$

where N_A – Avogadro constant; μ– molar mass.

Using formulas (7.1.2) and (7.1.3), we find the mass of the radioactive preparation:

$$m = \frac{A \cdot \mu}{N_A \cdot \lambda}. \qquad \text{(Eq. 7.1.4)}$$

In this laboratory to determine the activity of a radioactive source find the number of γ-quanta registered using the counter per unit time (I, imp/s). Given that, the radiation spreads uniformly in all directions, the counter whose cross-sectional area S, at a distance R from the source $S/4\pi R^2$ is part of the radiation (Fig. 7.1.2).

In addition, the counter detects only the portion of the radiation η that falls on it (η "counter efficiency"). Therefore, the counting rate of the counter γ-quanta is:

$$I = A\eta \frac{S}{4\pi R^2}, \qquad \text{(Eq. 7.1.5)}$$

where R – distance from the source to the counter.

The relation (Eq. 7.1.5) determines the radiation intensity at a point at the distance R from the source and is called the *law of inverted squares*: It can be seen from the relation (Eq. 7.1.5) that the graph of dependence I from R^{-2} is a straight line, the tangent of the angle of inclination of which to the axis is equal to:

$$\tan\alpha = A\eta \frac{S}{4\pi}. \qquad \text{(Eq. 7.1.6)}$$

It should be borne in mind that determined from the experiments, the reference speed also contains the value of the intensity I_N, due to the presence naturally-occurring background radiation. Therefore, the value of I in equation (7.1.5) should be calculated as the difference of values I_R and I_N, $I = I_R - I_N$.

Various charged particle detectors are used to detect radiation, which can be divided into counters and track detectors, ionization, spark and proportional cameras. This work uses a Geiger counter. This counter is a gas discharge, the principle of operation of which is based on the phenomenon of independent gas discharge, which will exist without external ionization of gas, if it is not forced to extinguish.

The counter is a thin-walled, usually glass, sealed cylindrical chamber 1

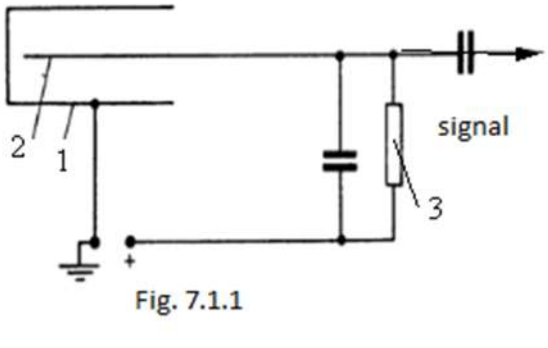

Fig. 7.1.1

(Fig. 7.1.1). The anode is a thin (about 0.05 mm diameter) metal thread 2 extended along the axis of the cylinder. Such an asymmetry in the electrode geometry causes the electric field to have high tension only in a small area around the anode filament and small in the rest of the space inside the counter.

The tube inside is filled with rarefied gas, most often argon or neon. When the γ-quanta of a radioactive isotope hit the walls of a counter, they knock out electrons that fall inside and move in the gas space. When they meet gas atoms, electrons ionize them (they form a free electron and a positive ion). The electric field between the cathode and the anode accelerates the electrons to the energies at which the impact ionization begins. An avalanche of ions occurs, and the current flowing through the counter increases sharply.

At the same time on the support 3 (Fig. 7.1.1) there is a voltage impulse, which is transmitted to the registration device. In order for the counter to be able to register the next particle that falls into it, the avalanche discharge must be quenched. This happens automatically, because at the moment of the appearance of the current impulse on the support there is a large voltage drop, so the voltage between the anode and the cathode sharply decreases so that the discharge disappears and the counter can again receive the impulse.

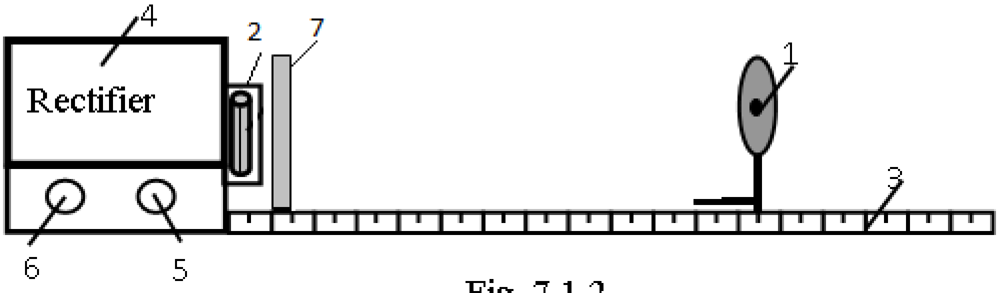

Fig. 7.1.2

Figure 7.1.2 shows the scheme of the experimental installation. Where 1 – is a radioactive source on a moving platform; 2 – Geiger counter; 3 – ruler; 4 – high-voltage rectifier; 5 – stopwatch; 6 – impulse counter; 7 – obstacle.

Pre-Laboratory Assignment

To perform the work, you need to study such a theoretical material: structure of the atomic nucleus; mass of the nucleus and charge; types of radioactive radiation; the radioactive decay law; displacement rules; methods of observation and registration of radioactive radiation.

Experimental Procedure

1. Turn on the power to the device.
2. Close the obstacle in front of the Geiger counter. Turn on the counter.
3. Measure the number of impulses N in a time τ of 3 minutes.
4. Set the source to the maximum distance from the counter and remove the obstacle.
5. Measure the number of pulses for a given distance within 3 minutes.
6. Repeat step 5 for different distances.
7. Write the results of measurements in Table 7.1.1 in Excel.

Calculations

1. Calculate the $I_N=N/\tau$ that matches the naturally-occurring background radiation.
2. Calculate the intensity I_R for each distance R.
3. Calculate the difference $I=I_R-I_N$ in Excel.
4. Construct I dependency graph from R^{-2} using the Excel with equation this function (Fig. 7.1.3).
5. Select two arbitrary points in the graph and calculate the slope tangent of the angle of the line:

$$\tan\alpha = \frac{I_2 - I_1}{\frac{1}{R_2^2} - \frac{1}{R_1^2}}. \qquad \text{(Eq. 7.1.7)}$$

6. Substituting the value $\mathrm{tg}\alpha$ into (Eq. 7.1.6), calculate the activity of the source:

$$A = \frac{4\pi \cdot \tan\alpha}{\eta \cdot S}. \qquad \text{(Eq. 7.1.8)}$$

7. Find the mass of radioactive source by the equations (7.1.8).
8. Make a report in the form of Excel table and graphs.

For calculations, take:

- the value of the half-life of the nucleus ^{32}P = 14.268 days;
- phosphorus molar mass μ=30.9 g/mol;
- «counter efficiency» η = 0.6.

Laboratory Report

Data and CalculationsTable7.1.1

R, m	N_N	N_R	I_N imp/s	I_R imp/s	*I* imp/s	*1/R*^{2} m^{-2}

Data and CalculationsTable7.1.2

tanα·	*η*	*S*, m^2	*A*, Bq	μ, kg/mol	$T_{1/2}$ c	λ Bq	*m*, kg

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Graph

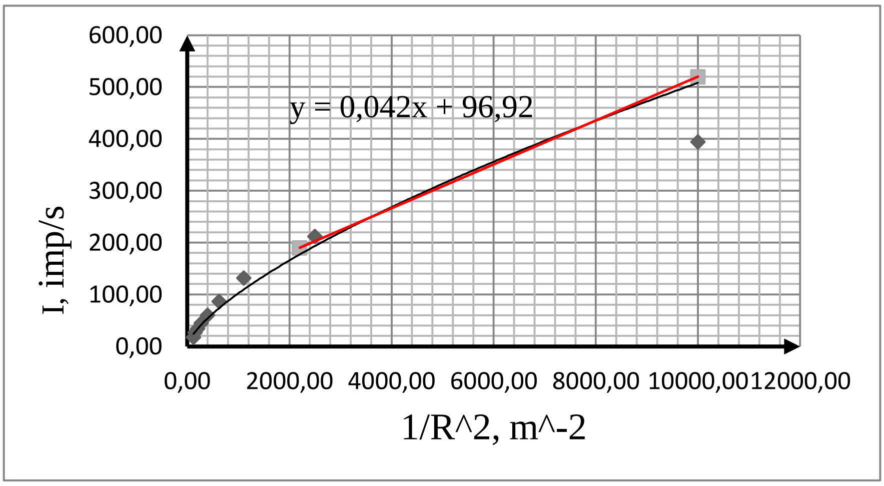

Fig. 7.1.3

Questions

1. What is radioactivity?
2. Name and describe the main types of radioactive transformations.
3. In the example of a nucleus $^{7}_{3}\mathrm{Li}$ describe the composition of the nucleus of any element.
4. What is an isotope? Name the isotopes of the hydrogen atom.
5. Write the reaction α - decay reaction $^{238}_{92}\mathrm{U}$.
6. What are the basic methods for registering ionizing radiation that you know?
7. Describe the structure of the Geiger counter and explain how it works.
8. State the law of radioactive decay.
9. What is the half-life of a radioactive source? How it is related to the decay constant?
10. What is the activity of a radioactive source?
11. Derive a formula for calculating the mass of a radioactive source and its activity.
12. What is the absorption and exposure dose of radiation? What are the units of measurement?

Laboratory 7.2

Determination of the Absorption Coefficient of Radioactive Radiation by Various Materials

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Objective:

- Study the main types of interaction of radioactive radiation with matter.
- Determine the absorption coefficient for gamma radiation in different types of materials.

Equipment List

- Geiger counter (single unit with Geiger tube, power supply, and timer)
- Absorber set (wood, ceramics, iron)
- Gamma source
- Lead screen

Theory

Radioactivity is the process of the spontaneous transformation of one atomic nucleus into another, which is accompanied by the emission of various particles. The highest penetrating ability has gamma radiation, which accompanies α and β decays in the process of nuclear transformation. When a gamma ray beam passes through matter, the gamma radiation intensity decreases mainly due to three processes: the *photoelectric effect*, *pair production*, and *Compton scattering*, each of which prevails at certain gamma radiation energies.

Let us consider these processes separately.

1. A *photoelectric effect* is the process of absorption of γ-quanta by a substance in which their energy is spent on the production of free electrons, which either leave the surface of the material (external photoelectric effect) or remain free charge carriers inside (internal photoelectric effect). This process is predominant among the three indicated types of interaction at low γ-ray energies. For example, photoelectric absorption is most significant in aluminum for energies $E_\gamma < 50$ keV, in lead for $E_\gamma < 0.5$ MeV.

2. As the energy of gamma quanta increases, the process of *Compton scattering* predominates – scattering of gamma quanta by free or weakly bound electrons (the binding energy of electrons in an atom is much less than the energy of gamma quanta). Due to the Compton effect, the energy of the scattered photon decreases, and the electron at which the scattering occurred acquires kinetic energy. This process prevails at γ-ray energies in aluminum of 60 keV $< E_\gamma <$ 15 MeV and in lead 0.7 MeV $< E_\gamma <$ 5.0 MeV.

3. *Pair formation* dominates these two processes at high γ-ray energies. The process consists in the fact that an electron-positron pair appears in the Coulomb field of a nucleus or a charged particle (which receives a fraction of the energy of a photon that interacts). The threshold of this reaction in the field of the heavy nucleus is $\approx 2m_ec^2 \approx 1.022$ MeV, and in the field of the electron $\approx 4m_ec^2$.

The change in the intensity of γ-radiation when passing through a substance is described by Bouguer's law:

$$I_x = I_0 e^{-\mu x}, \qquad \text{(Eq. 7.2.1)}$$

where I_x is the intensity of gamma radiation after passing through a layer of a substance of thickness x; I_0 is the initial intensity of gamma radiation; μ is the total linear absorption coefficient characterizing a decrease in the radiation intensity when passing through a substance. The units of linear absorption coefficient $[\mu] = 1\ m^{-1}$.

The total linear coefficient (linear coefficient) absorption determines the fate of monoenergetic gamma quanta that are eliminated from a parallel beam per unit radiation path in a substance. It depends on the density, serial number of the substance, and the energy of γ-quanta; therefore, it contains three components $\mu = \tau + \varepsilon + \chi$, where τ is the linear absorption coefficient in the case of the photoelectric effect, ε is the linear absorption coefficient for the Compton Effect, χ is the linear absorption coefficient for the pair formation process.

The main characteristics of the action of γ-radiation, as well as other types of ionizing radiation on a substance, are the absorbed, exposure, and biological doses of radiation and the dose rate.

The *absorbed dose* shows how much radiation energy is absorbed by a unit mass of the irradiated body. The SI unit of measure of absorbed dose is gray (Gy). One gray is the dose at which a substance of 1 kg transfers ionizing radiation energy of 1 J (or 1 Gy = 100 rad).

For air, the amount of radiation that causes ionization is called the *exposure dose*. It expresses the total charge of all ions of the same sign in the elementary volume of air relative to the mass of this volume. The off-system unit of measure of the exposure dose is roentgen (R), and in SI it is C/kg:

$$1\ R = 2.58 \cdot 10^{-4}\ C/kg.$$

It is important to measure the dose absorbed by biological material. To assess the degree of biological hazard, which depends on the type of ionizing radiation, the concept of an *equivalent dose* is introduced. The unit of measure of the equivalent dose of radiation is rem. One rem is the radiation dose, which is similar in its biological effect to the dose of x-ray irradiation in one roentgen.

To predict radioactive effects, the concept of *dose rate* has been introduced, which is used for both exposure dose and absorbed, equivalent doses. In each case, the corresponding power determines the dose that a substance receives per unit time.

Using the Equation 7.2.1, we can obtain a formula for determining the linear absorption coefficient of γ-radiation:

$$\mu = \frac{1}{x}\ln\frac{I_0}{I_x}. \qquad \text{(Eq. 7.2.2)}$$

It can be seen from the obtained formula that the linear absorption coefficient of gamma radiation by various materials is determined by measuring the radiation intensity I_x, which passes through different thicknesses x of the layer of matter placed between the gamma radiation source and the counter, as well as the *initial radiation intensity* I_0.

To obtain more accurate values of the gamma radiation intensity, it is recommended to subtract I_b from the obtained data I_x and I_0. I_b is the radiation intensity of the *natural background*, that is, radiation that the counter measures when the source of radiation is closed by a lead block.

Thus, the working formula takes the form:

$$\mu = \frac{1}{x}\ln\frac{I_0 - I_b}{I_x - I_b}. \qquad \text{(Eq. 7.2.3)}$$

If the density ρ of the test material is known, it is possible to determine the mass absorption coefficient, which is measured in $[\mu_m] = 1\ \text{m}^2/\text{kg}$:

$$\mu_m = \frac{\mu}{\rho}. \qquad \text{(Eq. 7.2.4)}$$

A diagram of the device for measuring the absorption coefficient is shown in Figure 7.2.1. It consists of lead block **1**, in which a radioactive source emitting almost parallel gamma rays is placed; a set of removable absorbers **2**, the absorption coefficient of which is determined in the lab; Geiger counter **3** (for a description, see lab 7.1); counting device **4**.

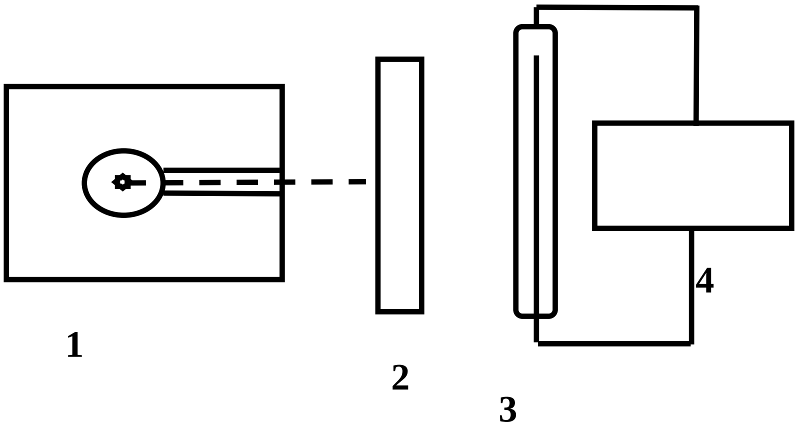

Fig. 7.2.1

Pre-Laboratory Assignment

To perform the work, you need to study such a theoretical material: radioactive radiation and its types; patterns of α, β and γ-decay and their properties; absorbed, exposure and biological doses, their units; dose rate.

Experimental Procedure

1. Close the radioactive source 1 with a lead screen 2.
2. Turn on the counting device 4.
3. Record the number of pulses N_b, due to the natural background, three times in one minute.
4. Open the lead screen and measure the number of pulses of the source N_0 three times in one minute.
5. Measure thickness of absorbers x (wood, ceramics, iron).
6. The test sample (wood, ceramics, iron) is placed between the source of radiation and the counter.
7. Make measurements of the number of pulses N_x in the same way (three times in one minute).
8. Record in Table 7.2.1 all results in Excel.

Calculations

1. Calculate the radiation intensity I_b, I_0 and I_x and find the average value in Excel.
2. Using the average values of I_b, I_0 and I_x, determine μ by the formula (7.2.3) and μ_m by the formula (7.2.4) in Excel.
3. Make a report in the form of Excel table.

Laboratory Report

Data and Calculations Table 7.2.1

	N	I, pulses/sec	$\langle I \rangle$, pulses/sec	x, m	μ, 1/m	μ_m, m^2/kg
Background						
Source						
Wood						
Iron						
Ceramics						

Questions

1. Tell about the composition of the nucleus of an atom.
2. What is called the binding energy and mass defect of the nucleus?
3. What is called radioactivity?
4. Formulate the law of radioactive decay.

5. What are the main types of ionizing radiation and describe their properties?
6. Write down the displacement rules for α and β decays.
7. What mechanisms of interaction of γ-radiation with matter are known to you? Under what conditions is each of these interaction mechanisms possible?
8. What is called absorbed, exposure, biological radiation dose, dose rate?
9. Formulate and explain Booger's law.
10. What is the physical meaning of linear and mass absorption coefficients?
11. Derive a formula that allows you to determine the relationship between the linear absorption coefficient and the thickness of the material.

Appendix

The main units of the International System (SI)

Length	**Mass**	**Time**	**Electric current**	**Thermodynamic temperature**	**Amount of substance**	**Luminous intensity**
Meter, m	Kilogram, kg	Second, s	Ampere, A	Kelvin, K	Mole, mol	Candela, cd

Some Physical constant

Quantity	**Symbol**	**Value**
Gravitational constant	$\mathbf{G}$	$6.673\cdot10^{-11}$ N·m^{2}/kg^{2}
Avogadro constant	N_{A}	$6.022\cdot10^{23}$ mol^{-1}
Molar gas constant	R	8.315J·mol^{-1}·K^{-1}
Molar volume of an ideal gas	V_m	$22.414\cdot10^{-3}$ m^{3}
Permittivity of free space	ε_0	$8.854\cdot10^{-12}$ F·m^{-1}
Permeability of vacuum (or magnetic constant)	μ_0	$4\pi\cdot10^{-7}$ H/m = $12.566\cdot10^{-7}$ H/m
Boltzmann constant	k	$1.380\cdot10^{-23}$ J/K
Faraday constant	F	$9.649\cdot10^{-4}$ C·mol^{-1}
Stefan constant	σ	$5.669\cdot10^{-8}$ W·м$^{-2}$·К$^{-4}$
Wien's displacement constant	b	$2.897\cdot10^{-3}$ m·K
Planck constant	h	$6.626\cdot10^{-34}$ J·s
Charge-to-mass ratio of electron	e/m_c	$1.759\cdot10^{-11}$ C/kg
Elementary charge	e	$1.602\cdot10^{-19}$ C
Speed of light in a vacuum	c	$2.997\cdot10^{8}$ m/s
Bohr radius	a_0	$0.529\cdot10^{-10}$ m
Electron rest mass	m_{e}	$9.109\cdot10^{-31}$ kg = $5.49\cdot10^{-4}$ u
Proton rest mass	m_p	$1.672\cdot10^{-27}$ kg = 1.00727 u
Neutron rest mass	m_n	$1.675\cdot10^{-27}$ kg = 1.00866 u
Rydberg constan (for hydrogen atom)	R_H	$1.097\cdot10^{7}$ m^{-1}
Compton wavelength	λ_c	$2.426\cdot10^{-12}$ m
Bohr magneton	μ_{B}	$9.274\cdot10^{-24}$ J·T^{-1}
Ionization energy (for hydrogen atom)	W_i	$2.18\cdot10^{-18}$ J

Some extra-system values

1° = $1.75\cdot10^{-2}$ rad	1 year = 365 days = = $3.11\cdot10^{7}$ s	Å – Angstrom (10^{-10})
1 mm Hg.Art. = 133.3 Pa	1 day = 86400 s	1 eV = $1.6\cdot10^{-19}$ J
cal = 4.18 J	1 kWh = $3.6\cdot10^{6}$ J	1 Ki (Curie) = $3.7\cdot10^{10}$ Bq

Thermal Conductivity of Solids and Metals, W/(mK)

Oak wood	0.175	Felt	0.046
Brick	0.55…0.84	Dry sand	0.325
Aluminum	210	Stopper	0.050
Iron	58.7	Scaling in boilers	0.60
Copper	390	Ebonite	0.174
Felt	0.046	Fused quartz	1.37

Work function of electrons from metals

Metal	W, J	W,eV
Potassium	$3.5\cdot10^{-19}$	2.2
Lithium	$3.7\cdot10^{-19}$	2.3
Platinum	$10.0\cdot10^{-19}$	6.3
Rubidium	$3.4\cdot10^{-19}$	2.1
Silver	$7.5\cdot10^{-19}$	4.7
Cesium	$3.2\cdot10^{-19}$	2.0
Zinc	$6.4\cdot10^{-19}$	4.0

Half-attenuation layer thicknesses and absorption coefficients γ-rays by some materials

Material	The thickness of the layer is half attenuated, m	The linear absorption coefficient, m^{-1}	The mass attenuation coefficient, m^2/kg
Concrete (density $3{,}2\cdot10^{3}$kg/m^3)	0.10	6.93	$2{,}17\cdot10^{-3}$
Steel (armor)	0.03	23.11	$2{,}96\cdot10^{-3}$
Lead	0.02	34.66	$3{,}06\cdot10^{-3}$

List of SI prefixes

E – exa (10^{18})	M – mega (10^{6})	c – centi (10^{-2})	p – pico (10^{-12})
P – peta (10^{15})	k – kilo (10^{3})	m – milli (10^{-3})	f – femto (10^{-15})
T – tera (10^{12})	h – hekto (10^{2})	μ – micro (10^{-6})	a – atto (10^{-18})
G – giga (10^{9})	d – deci (10^{-1})	n – nano (10^{-9})	

A Density of Substances (kg/m^3)

Substance	**Density**	**Substance**	**Density**
Aluminum	$2.7\cdot10^3$	Cork	$0.22\ldots0.26\cdot10^3$
Brass	$8.4\cdot10^3$	Oak wood	$0.60\ldots0.90\cdot10^3$
Copper	$8.9\cdot10^3$	Maple wood	$0.62\ldots0.75\cdot10^3$
Gold	$19.3\cdot10^3$	Pine wood	$0.35\ldots0.50\cdot10^3$
Iron	$7.85\cdot10^3$	Alcohol, ethyl	$0.79\cdot10^3$
Lead	$11.3\cdot10^3$	Alcohol, methyl	$0.81\cdot10^3$
Nickel	$8.7\cdot10^3$	Mercury	$13.6\cdot10^3$
Steel	$7.8\cdot10^3$	Pure water	$1.000\cdot10^3$
Zinc	$7.1\cdot10^3$	Sea water	$1.025\cdot10^3$

The Greek Alphabet

Alpha	Α	α	Iota	Ι	ι	Rho	Ρ	ρ
Beta	Β	β	Kappa	Κ	κ	Sigma	Σ	ς
Gamma	Γ	γ	Lambda	Λ	λ	Tau	Τ	t
Delta	Δ	δ	Mu	Μ	μ	Upsilon	Υ	υ
Epsilon	Ε	ε	Nu	Ν	ν	Phi	Φ	φ
Zeta	Ζ	ζ	Xi	Ξ	ξ	Chi	Χ	χ
Eta	Η	η	Omicron	Ο	ο	Psi	Ψ	ψ
Theta	Θ	θ	Pi	Π	π	Omega	Ω	ω

Standard Abbreviations and Symbols for Units

Symbol	**Unit**	**Symbol**	**Unit**
A	ampere	K	kelvin
u	atomic mass unit	kg	kilogram
atm	atmosphere	kmol	kilomole
Btu	British thermal unit	L	liter
C	coulomb	lb	pound
^{o}C	degree Celsius	ly	light-year
cal	calorie	m	meter
d	day	min	minute
eV	electron volt	mol	mole
^{o}F	degree Fahrenheit	N	newton
F	farad	Pa	pascal
ft	foot	rad	radian
G	gauss	rev	revolution
g	gram	s	second
H	henry	T	tesla
h	hour	V	volt
hp	horsepower	W	watt
Hz	hertz	Wb	weber
in.	inch	yr	year
J	joule	O	ohm

Solar System Data

Body	Mass (kg)	Mean Radius (m)	Period (s)	Distance from the Sun (m)
Mercury	$3.18\cdot10^{23}$	$2.43\cdot10^{6}$	$7.60\cdot10^{6}$	$5.79\cdot10^{10}$
Venus	$4.88\cdot10^{24}$	$6.06\cdot10^{6}$	$1.94\cdot10^{7}$	$1.08\cdot10^{11}$
Earth	$5.98\cdot10^{24}$	$6.37\cdot10^{6}$	$3.156\cdot10^{7}$	$1.496\cdot10^{11}$
Mars	$6.42\cdot10^{23}$	$3.37\cdot10^{6}$	$5.94\cdot10^{7}$	$2.28\cdot10^{11}$
Jupiter	$1.90\cdot10^{27}$	$6.99\cdot10^{7}$	$3.74\cdot10^{8}$	$7.78\cdot10^{11}$
Saturn	$5.68\cdot10^{26}$	$5.85\cdot10^{7}$	$9.35\cdot10^{8}$	$1.43\cdot10^{12}$
Uranus	$8.68\cdot10^{25}$	$2.33\cdot10^{7}$	$2.64\cdot10^{9}$	$2.87\cdot10^{12}$
Neptune	$1.03\cdot10^{26}$	$2.21\cdot10^{7}$	$5.22\cdot10^{9}$	$4.50\cdot10^{12}$
Pluto	$1.4\cdot10^{22}$	$1.5\cdot10^{6}$	$7.82\cdot10^{9}$	$5.91\cdot10^{12}$
Moon	$7.36\cdot10^{22}$	$1.74\cdot10^{6}$	—	—
Sun	$1.991\cdot10^{30}$	$6.96\cdot10^{8}$	—	—

Physical Data Often Used

Average Earth-Moon distance	$3.84\cdot10^{8}$ m
Average Earth-Sun distance	$1.496\cdot10^{11}$ m
Average radius of the Earth	$66.37\cdot10^{6}$ m
Density of air (20 ◦C and 1 atm)	1.20 kg/m^{3}
Density of water (20 ◦C and 1 atm)	$1.00\cdot10^{3}$ kg/m^{3}
Free-fall acceleration	9.80 m/s^{2}
Mass of the Earth	$5.98\cdot10^{24}$ kg
Mass of the Moon	$7.36\cdot10^{22}$ kg
Mass of the Sun	$1.99\cdot10^{30}$ kg
Standard atmospheric pressure	$1.013\cdot10^{5}$ Pa

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Навчальне видання

ПАНОВА Олена Василівна
АЗНАУРЯН Ірина Олександрівна
КРАСНЯНСЬКИЙ Григорій Юхимович та ін.

Ф І З И К А

ЛАБОРАТОРНИЙ ПРАКТИКУМ

Навчальний посібник
із використанням пакету Excel
(англійською мовою)

Містить навчальні матеріали для виконання лабораторних робіт базового рівня за допомогою пакету Excel. Матеріал представлений англійською мовою для використання студентами, які вільно ним володіють або хочуть покращити свої знання англійської мови, та іноземними студентами. Призначений для студентів усіх спеціальностей KNUCA.

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