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LABORATORY MANUAL
Physics

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PREFACE

Physics as any other natural science investigates the properties of nature – the properties of surrounding world. It tries to answer the questions about the behaviour of light and matter, the two things that the universe is made of.

Every natural science including physics is based on scientific method whose main principles are:

1. Science is a cycle of theory and experiment.

Scientific theories are created to explain the results of experiments that were created under certain conditions. A successful theory will also make new predictions about new experiments under new conditions. Eventually, though, it always seems to happen that a new experiment comes along, showing that under certain conditions the theory is not a good approximation or is not valid at all. If an experiment disagrees with the current theory, the theory has to be changed, not the experiment.

2. Theories should both predict and explain.

The requirement of predictive power means that a theory is only meaningful if it predicts something that can be checked against experimental measurements that the theorist did not already have at hand. That is, a theory should be testable. Explanatory value means that many phenomena should be accounted for with few basic principles. If you answer every “why” question with “because that’s the way it is,” then your theory has no explanatory value. Collecting lots of data without being able to find any basic underlying principles is not science.

3. Experiments should be reproducible.

An experiment should be treated with suspicion if it only works for one person, or only in one part of the world. Anyone with the necessary skills and equipment should be able to get the same results from the same experiment.

Researchers in many fields understand the need for data to be gathered in a certain consistent manner, and to be manipulated in an equally constant way - a way which allows useful theories, theorems, etc, to be derived from it. Although the actual experimental equipment and the theories which generated the decision to do the experiment vary by discipline, the basic principles and procedures are the same. You must look at data and results with a critical, educated eye - one which has been trained in the scientific method. The ability to critically analyze any situation is a skill which repeatedly proves useful to everyone at one time or another.

This manual is for the laboratory portion of the Physics lecture course. This introduction will enumerate rules and procedures for the lab. You will learn how to determine the most common sources of error in experimental data. Also, you will learn how to graphically represent data and how to use it for further analysis.

Laboratory 1

INTRODUCTION TO LABORATORY MANUAL

1.1. RECORDING DATA

1.1.1. Units

In most sciences, the common unit system in use is the metric MKS (*m*eters, *k*ilograms, *s*econds) system. Less common is the metric CGS (*c*entimeters, *g*rams, *s*econds) system. Sometimes we use some specific units, for example, mm. Hg. – millimeter of mercury column, $\overset{o}{A}$ - angstrom, etc.

1.1.2. Significant figures

Data manipulation requires a certain amount of finesse when you are mathematically combining values that have different amounts of significant figures. The *least significant figure* is the value in the lowest decimal place you actually know, as opposed to just being a place-holder, and is the number which dictates how many decimal places you keep during mathematical combination. For addition/subtraction there is one rule, for multiplication/division another.

Addition/subtraction: when adding numbers with different significant figures, keep one more decimal place past the least significant digit, and then round off when the calculation is finished.

Example: 125,75 cm + 91 cm + 100,0 cm = ?

$$\begin{array}{rl} & 125{,}75 \text{ cm} \\ + & 91 \text{ cm} \\ & \underline{100{,}0 \text{ cm}} \\ \sim & 316{,}8 \text{ cm} \end{array}$$

But when reporting this answer, you need to consider both significant figures and round-off. The least significant figure of the three is the “1” in 91 so the answer will be reported with three digits only. Next consider round-off. The fourth digit is an 8, so the final reported answer is: 317. Convince yourself that this is indeed the right answer.

Multiplication/division: the rule is to count the actual number of significant figures in each value being multiplied, and then keep the number of significant figures as the value with the smallest number of them.

1.2. ERROR ANALYSIS

Most lab situations concern themselves with taking, processing, and analysis of data from which theory is derived, supported, or disproved. It is always wise to understand the limits inherent in your numbers, for if there is one thing that is certain in this universe, it is that “nothing is exact”. So if nothing is exact, just how close to exact is your data?

1.2.1. Instrument errors

All measuring tools have error associated with them, usually known as the instrument’s *precision*.

1. Using a meter stick, measure the width of your lab table and record it in your answer sheet.
2. What is the smallest unit on your meter stick? (in mm? in cm? in m?)
3. Can you say that the measurement of the table’s width is closer to one (of the smallest) marks than another?

The smallest increment you can read on your instrument is known as the *least count* of that instrument. For the meter stick, the least count is the value recorded in 2. The definition of instrumental uncertainty for any instrument is simply 1/2 multiplied by the least count of that instrument.

4. What is the meter stick’s measurement uncertainty? Does this make sense?

Any one else should be able to look at data you’ve taken and without knowing details of the experiment understand how exact it is, and what the units are. The uncertainty, Δx_i, must always be recorded with the value itself, x_i and units must be included:

$x_i \pm \Delta x_i$.

5. In the correct format, write down the width of the table and its uncertainty. Remember the units.

1.2.2. Fractional and percent deviation

The fractional deviation answers the question "what fraction of the value is the uncertainty?" and is given by $\frac{\Delta x}{x}$. The percent error is simply $100 \cdot \frac{\Delta x}{x}$.

1.2.3. Propagation of error through calculations

In general errors are of an additive nature, but to simply add them overestimates the deviation. As with significant figures, there are rules for addition/subtraction, multiplication/division, and here we add a rule for powers. These rules are presented without proof for everyone's collective sanity.

Addition and Subtraction: Let *C* = *A* + *B* or *C* = *A* - *B*. Then the square of the error after addition or subtraction in both cases is the *sum* of the squares of the input errors. Mathematically, we write

$$\Delta C = \sqrt{(\Delta A)^2 + (\Delta B)^2}.$$

Multiplication and Division: Let *C* = *A* · *B* or *C* = *A*/*B*.

The key to errors in multiplication and division is to look at the fractional errors:

$$\frac{\Delta C}{C} = \sqrt{\left(\frac{\Delta A}{A}\right)^2 + \left(\frac{\Delta B}{B}\right)^2}.$$

Powers: Let $A = B^n$, then the fractional error of A is given as:

$$\frac{\Delta A}{A} = n\sqrt{\left(\frac{\Delta B}{B}\right)^2} = \frac{n\Delta B}{B}.$$

1.2.4. Repeated measurements and the mean

When you have a group of n repeated measurements, it makes sense to calculate the average value, or *mean value* for that group. The *mean*, is simply the sum of all n values, divided by the number of values in the group:

$$\overline{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \, .$$

The mean, too, must always be recorded with its associated error. But what is the error of the mean?

1.2.5. The error in the mean: the standard deviation

What would be a logical way to discuss the error associated with the mean of a group of values? Each value was taken with the same instrument, perhaps just the uncertainty in the measurements would suffice. Alas, no. Typically the mean deviates from the data by a value not simply related to the uncertainty. A better way would be to determine the average deviation of each individual data point from the calculated mean. This is essentially the definition of universe standard.

Deviation of the mean, or more simply - the *standard deviation*, σ_n:

$$\sigma_n = \sqrt{\left[\frac{1}{n}\sum_{i=1}^{n}(x_i - \overline{x})^2\right]} \, .$$

1.3. EXPERIMENTAL ERROR

Errors associated with experiments may be summarized by 3 types:

1. *Systematic errors*.

These include prejudice on the part of the observer, inherent defects in equipment, neglect of effects such as temperature, pressure, humidity, etc. These errors are characterized by their tendency to be in only one direction. For example, if a meter stick is slightly worn at one end and measurements are taken from this end, then a constant error will occur in all measurements. Unknown systematic errors can only be discovered by comparing measurements of the same physical quantity which are obtained by several methods.

2. *Personal errors.*

Error due to blunders, such as mistakes in arithmetic, in recording data, or in reading measurements. These can be minimized by repeating measurements and keeping redundant record which are subject to cross-checks.

3. *Random errors.*

A series of measurements in which the systematic errors have been minimized will still contain variation due to causes that lie beyond the control of the observer. These are characterized by discrepancies in several measurements of a quantity under apparently identical conditions. It is assumed that they are due to the combined effect of a great number of independent causes, each of which is equally likely to produce a positive or negative effect. Random errors are statistical in nature and therefore can be analyzed by statistical methods.

1.4. GRAPHING DATA. GRAPHICAL "SYNTAX"

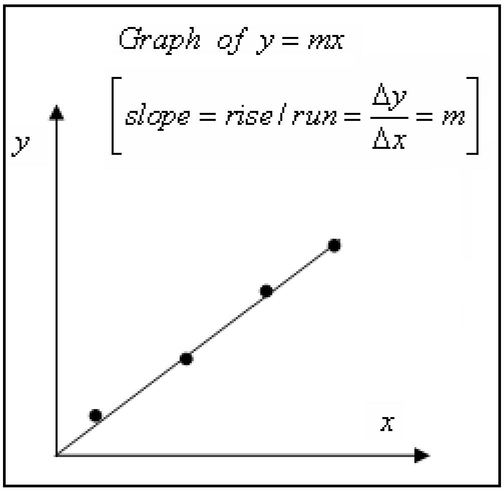
Graphical analysis of a data set is an extremely useful tool to the scientist. Often the general shape of the curve described by the data gives clues to whether: you did the experiment properly, if your data supports the theory. Properties of lines and curves can give you information about the theory from a set of graphed data as well. Thus it's important we're all speaking the same language with respect to graphs.

Before attempting to construct a graph, your data must be organized into a clear and easily readable form. It is usually desirable to put your data into the form of a table, clearly indicating what was measured, the units and comments about experimental uncertainties. If some data seems to clearly disagree with the rest, put a question mark next to it, but do not eliminate it at this time. A graph can present a clear picture of how one physical quantity depends on another. However, to be effective, a graph must conform to accepted rules. In order to display the information clearly, choices must be made concerning the size of the graph, scale for each axis, appropriate use of symbols and words and the type of graph (linear, semi-logarithmic, etc.). The rules presented below are followed by most scientists and engineers.

1. Use graph paper or an acceptable substitute.

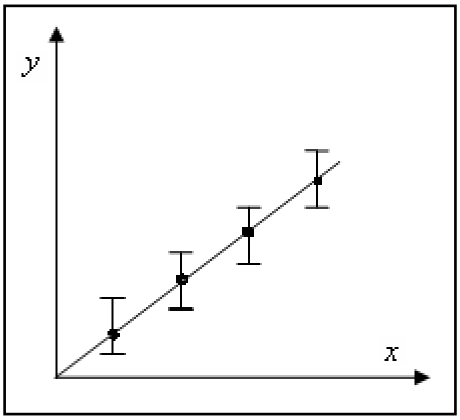
2. Data taken in the labs are often accurate to three significant figures. The graph should be made as large as possible in order to retain this accuracy. Scales for the coordinate axes should be chosen so that the data extends over almost all of a full-sized sheet of paper. It may be necessary to suppress the zero so that the data and the resulting curve will cover most of the graph paper. The decimal parts of units should be easily located. This can be done if each small division is made equal to numbers such as 0,1, 0,2, or 0,5.

3. The scale need not be the same on both axes; however, each axis *must be labelled* by the quantity and units being plotted and the division used. The units of the measured quantities are customarily enclosed in parentheses. If velocity is being measured in m/s, use *v* (m/s). The use of a power of 10 in a scale caption in the form "*v* in m/s $\times 10^3$ "or "*v* $\times 10^3$ m/sec" should be avoided since it is not clear whether the scale numbers have been or are to be multiplied by 10^3. To avoid misunderstanding when it is necessary to use a factor like 10^3, it should be directly associated with the units as $v(10^3$ m/s) or directly associated with the scale numbers.



4. A brief caption may be inserted in a vacant area within the graph to make the graph reasonably self-explanatory. All symbols used in the graph should be explained. Make sure the graph is titled.

5. In plotting a curve, the *dependent* variable is plotted along the *vertical* axis and the *independent* variable is plotted along the *horizontal* axis. For example, a straight line through the origin with slope *m* is represented by the equation $y = m\,x$. A plot of this line is shown in the figure.



6. Technically, actually connecting graphed points with a solid line/curve indicates that you know that the values between your data points lie along that curve, that it is a fact and you are certain. Dashed or dotted lines/curves indicate you believe the theory to hold between the data points but you don't have the data. Best-fit and theoretical lines or curves are drawn through a group of data points and are labelled as exactly that - best-fit or theoretical, not exact. This may appear a technicality, but it is part of the graphical language science shares and it's wise to adhere to it.

7. A best-fit or theoretical smooth curve should be drawn in such a way as to fit the points as closely as possible within the error bars and, in general, as many points will be on one side of the curve as on the other. The extent to which the plotted points coincide with the theoretical curve is a measure of the precision of the results.

8. If the experimental points lie along a straight line, the location of the "best fit" line can often easily be found by sighting along the points when the eye is placed almost in the plane of the paper (eye-ball fit).

1.5. DETERMINATION OF THE ERRORS OF INDIRECT MEASUREMENTS

Measurement the table width by a meter stick is direct measurement and the determination of acceleration due to gravity according to the expression

$$g = \frac{4\pi^2 l}{T^2} = \frac{4\pi^2 \cdot l \cdot N}{t^2}$$

is an example of indirect measurements. We directly measure N (the number of oscillations), l (simple pendulum length) and t (the period of time of N oscillations). The errors of their measurements are: for N: 1 oscillation; for l: 0,5 mm (1/2 multiplied by the least count of ruler) and for t: 0,5 s (the period of time corresponded to our reaction for fixing the pendulum position not the accuracy or least count of the clocks).

For $\Delta g / g$ finding let us carry out the following:

1. Take the logarithm of the formula:

$$\ln g = \lg 4 + 2\ln \pi + \ln l + \ln N - 2\lg t\,;$$

2. Differentiate this expression considering the measured magnitudes as variables and known magnitudes as constants:

$$\frac{dg}{g} = \frac{dl}{l} + \frac{dN}{N} - 2\frac{dt}{t}\,;$$

3. Change all minuses by pluses and put Δ instead of d:

$$\frac{\Delta g}{g} = \frac{\Delta l}{l} + \frac{\Delta N}{N} + 2\frac{\Delta t}{t}\,.$$

Submitting the magnitudes of the errors and the means of measured *l*, *N* and *t*, we obtain

$$\frac{\Delta g}{g} = \frac{\Delta l}{l} + \frac{\Delta N}{N} + 2\frac{\Delta t}{t} = \frac{0,5\cdot 10^{-3}}{0,5} + \frac{1}{25} + 2\frac{0,1}{20} =$$
$$= 0,001 + 0,04 + 0,01 = 0,051 \approx 0,06.$$

Pay your attention that the round-off is made by increasing the obtained value (independent on mathematical rules for round-off).

As $\frac{\Delta g}{g} = 0,06$ and the mean of *g* obtained from experiment is 9,8 m/s^2, then

$$\Delta g = 9,6\cdot 0,06 = 0,576 \approx 0,6 \text{ m/s}^2,$$

and the final result is

$$g = 9,6 \pm 0,6\,\text{m/s}^2.$$

MECHANICS

Laboratory 2 (8*- M)

DETERMINATION OF ACCELERATION DUE TO GRAVITY BY MEANS OF SIMPLE PENDULUM

Purpose:

To determine the acceleration due to gravity by means of investigation of physical pendulum motion.

Theory:

A *simple pendulum* is a material point of mass m attached to the end of long weightless inextensible thread. Another end of it is attached to the fixed point. If the mass is displaced slightly, it begins to oscillate to-and-fro along the arc of a circle in a vertical plane. The period of oscillations is $T = 2\pi\sqrt{\frac{l}{g}}$, where l is the length of the pendulum and g is the acceleration due to gravity.

Notice that T is independ on the mass of pendulum. This expression for T is accurate only if the amplitude of the swing is small (deflection angle is less than 5°). For big swings, T is slightly larger than given by this equation.

The determination of the acceleration due to gravity can be done by two methods.

1) Expressing g from the formula of period and taking into account that $T = \frac{t}{N}$, where t is the time of N oscillations, we obtain

$$g = \frac{4\pi^2 l}{T^2} = \frac{4\pi^2 \cdot l \cdot N}{t^2}.$$

2) Calculation of g using a slope angle of the straight line representing the dependence $T^2(l)$.

Materials:

The simple pendulum, the meter stick, and the stopwatch.

Procedure:

1. Adjust the length *L* of your pendulum to be close to 1,00 m and measure it as precisely as you can with a meter stick. (Think about how best to measure the distance to the center of the mass.)

2. Set the pendulum swinging with small amplitude swings. Determine the period *T* by using the stopwatch to measure the time for *N* complete swings, and then dividing it by *N*.

3. Repeat this procedure for five different lengths.

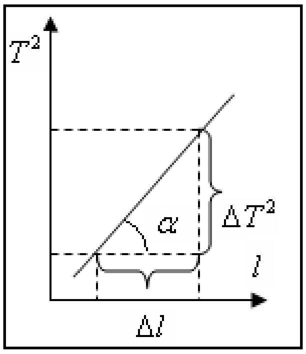
4. Calculate acceleration due to gravity for each experiment and find the mean magnitude $\overline{g}$.

5. Record the results of measurements into the table.

l , m	t, s	N	T, s	g, m/s^2	$\overline{g}$, m/s^2

6. Make the plot $T^2(l)$

7. Determine the tangent of the slope angle of a straight line $T^2(l)$.



$$\mathrm{tg}\alpha = \frac{\Delta T^2}{\Delta l}.$$

8. Find the acceleration due to gravity according the expression

$$g = \frac{4\pi^2}{\mathrm{tg}\alpha} .$$

7. Estimate the errors of your results.

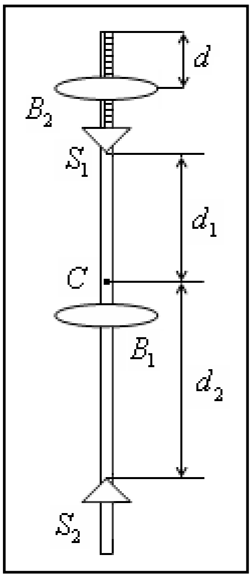
Laboratory 3 (8-M)

DETERMINATION OF ACCELERATION DUE TO GRAVITY BY MEANS OF PHYSICAL PENDULUM

Purpose:

To determine an acceleration due to gravity by means of investigation of physical pendulum motion.

Theory:



A *physical (compound) pendulum* is a rigid body oscillating around a horizontal axis passing through the *point of suspension* located above its center of mass.

The period of physical pendulum is $T = 2\pi\sqrt{I/mgx}$, where I is the moment of inertia about the axis of oscillations, *m* is the pendulum mass, *g* is the acceleration due to gravity, *x* is the distance between a center of mass and a pivot point.

This formula may be simplified introducing the length of an equivalent simple pendulum (equivalent length) $L = I/mx$. Equivalent simple pendulum has a same period of oscillations as the physical pendulum.

Hence, the period of oscillations can be determined as $T = \sqrt{L/g}$.

We use reversible (Kater's) pendulum in this experiment. It consists of two bobs (immovable B_1 and movable B_2) on the rod. There are two supports: S_1 and S_2.

An application of the reversible pendulum for the determination of the acceleration due to gravity is based on the following property: in a certain position of the movable bob B_2 the periods (T_1, T_2) of the pendulum supporting on the S_1 and S_2 are equal to each other. Therefore, the distance between the supports is the equivalent length.

$$T_1 = T_2 = T = 2\pi\sqrt{\frac{I_1}{mgd_1}} = 2\pi\sqrt{\frac{I_2}{mgd_2}}\ .$$

The requirement of this equality is the equality of the equivalent lengths in two positions of the pendulum, i.e., $\frac{I_1}{md_1} = \frac{I_2}{md_2}$. According to the parallel axis theorem (Steiner's theorem)

$$I_1 = I_C + md_1^2; \quad I_2 = I_C + md_2^2\ .$$

Consequently,

$$g = \frac{4\pi^2}{T^2}\left(d_1 + d_2\right),$$

where $\left(d_1 + d_2\right)$ is the distance between the supports.

The accurate determination of the position of the movable bob when the periods are the same may be carried out by means of a plot $T\left(d\right)$, where d is the position of bob B_2, for two positions of the pendulum (movable bob is above and under the center of oscillations).

Materials:

Reversible pendulum, the stopwatch, and the meter stick.

Procedure:

1. Put the pendulum on the support S_1 and measure the period of time *t* for *N* oscillations. Repeat this procedure for 5 positions of movable bob.

2. Put the pendulum on the support S_2 and make the same measurements.

3. Wright down your results in the table.

N	d, m	"above"		"under"	
		t_1, s	T_1,s	t_2,s	T_2,s

4. Plot two dependencies $T_1(d)$ and $T_2(d)$ on linear graph paper using one coordinate frame. Find the intersection point of two graphs.

5. Check out experimentally whether the found period T is corresponded to the found d.

6. Measure the distance between the supports $(d_1 + d_2)$ and find the acceleration due to gravity

$$g = \frac{4\pi^2}{T^2}(d_1 + d_2)$$

7. Estimate the errors and make the conclusion.

Laboratory 4 (5-M)

CHECKOUT OF NEWTON'S 2ND LAW FOR ROTATIONAL MOTION

Purpose:

The experimental checkout of the validity of Newton's 2nd law for rotational motion.

Theory:

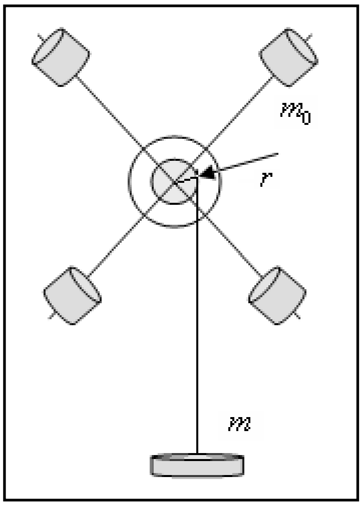
Newton's 2nd law for rotation is

$$\vec{M} = I\vec{\varepsilon},$$

where $\vec{M}$ is the torque, I is the moment of inertia of the object, $\vec{\varepsilon}$ is its angular acceleration.

The corollary of this law for constant moment of inertia is

$$\frac{\varepsilon_1}{M_1} = \frac{\varepsilon_2}{M_2};$$



The experimental installation is the cross pendulum consisting of two sheaves (disks) with four rods. The plumbs of mass m_0 are on the rods. Their distances from the pivot point can be changed. The weight of mass m is attached to the tread which can be reeled up on any of the sheaves.

The torque applied to the cross pendulum is equal to $M = Tr$,where T is the tension of the thread and r is the radius of the sheave.

According to Newton's 2nd law $T = mg - ma$.

The weight falling down from the height h during the period of time t has the acceleration $a = \frac{2h}{t^2}$. The thread which part is moving at the angular acceleration $\varepsilon = \frac{a}{r} = \frac{2h}{rt^2}$ has the linear acceleration as the weight.

Hence, the torque is $M = mr\left(g - \frac{2h}{rt^2}\right)$.

Materials:

The cross pendulum, four plumbs of mass m_0, the set of weights of mass m, the stopwatch and the meter stick.

Procedure:

1. Fix the plumbs at equal distances from the pivot point of the pendulum.
2. Reel up the thread on one of the sheaves.
3. Let off the weight m.
4. By means of stopwatch determine the time of weight motion along the last 1 m of the height.
5. Repeat the experiment changing the weight m and the sheave.
6. Write down your results in the table.

m, kg	r, m	h, m	t, s	M, N·m	ε, s^{-2}

7. Compare the relationship $\frac{\varepsilon_1}{M_1} = \frac{\varepsilon_2}{M_2}$, estimate the errors and make the conclusions.

Laboratory 5 (3-M)

INVESTIGATION OF ELASTIC AND INELASTIC COLLISIONS OF TWO SPHERES

Purpose:

To investigate the elastic and inelastic collisions of two spheres for verifying the law of conversation of linear momentum.

Theory:

The collision is the assemblage of phenomena taking place during the contact of moving objects.

The period of collision time is $\sim 10^{-4} - 10^{-5}$ s. The collision process consists of two phases. The first phase begins at the moment of touching objects and ceases in the moment of finishing of their approach. To this moment the kinetic energy transforms into the potential energy of deformation. The second phase is the reverse process: the transition of potential energy (or the part of it) into the kinetic energy.

During the elastic collision the laws of conservation of energy and momentum are verified.

During the inelastic collision only the law of conservation of momentum is verified. The mechanical energy isn't conserved as the part of kinetic energy has been transformed into the energy of plastic deformation energy.

Application of the laws of conservation allows finding the velocities of objects m_1 and m_2 after the collision ($\vec{u}_1$ and $\vec{u}_2$) if their velocities before collision ($\vec{v}_1$ and $\vec{v}_2$) are known.

For elastic collision :

$$m_1\vec{v}_1 + m_2\vec{v}_2 = m_1\vec{u}_1 + m_2\vec{u}_2,$$

$$\vec{u}_1 = \frac{2m_2\vec{v}_2 + (m_1 - m_2)\vec{v}_1}{m_1 + m_2}; \quad \vec{u}_2 = \frac{2m_1\vec{v}_1 + (m_2 - m_1)\vec{v}_2}{m_1 + m_2}.$$

For inelastic collision ($\vec{u}$ is the velocity of combined object of mass $m_1 + m_2$):

$$m_1\vec{v}_1 + m_2\vec{v}_2 = (m_1 + m_2)\vec{u},$$

$$\vec{u} = \frac{m_1\vec{v}_1 + m_2\vec{v}_2}{m_1 + m_2}.$$

In this experiment we want to study the collision of a moving sphere with a stationary sphere.

For elastic collision when the object of mass m_2 is at rest, the law of conservation of linear momentum is

$$m_1 v_1 = m_2 u_2 - m_1 v_1.$$

If l is the length of the thread, the speeds of the spheres can be expressed as

$$v_1 = 2\sqrt{gl}\sin\frac{\alpha_0}{2};\quad u_1 = 2\sqrt{gl}\sin\frac{\beta}{2};\quad u_2 = 2\sqrt{gl}\sin\frac{\alpha}{2},$$

where α_0, α, β are the deflection angles of the spheres.

Hence the law of conservation of linear momentum for elestic collision is

$$m_1\sin\frac{\alpha_0}{2} = m_2\sin\frac{\beta}{2} - m_1\sin\frac{\alpha}{2}. \qquad (1)$$

Sign “-“ in the right part of equation we have choosen as the first sphere after the collision moves in the reverse direction.

For inelastic collision the law of conservation of linear momentum is

$$m_1\sin\frac{\alpha_0}{2} = (m_1 + m_2)\sin\frac{\gamma}{2}, \qquad (2)$$

where γ is the deflection angle of the centre of mass of two spheres having sticked together.

Materials:

Elastic and nonelastic spheres of equal and unequal masses.

Procedure:

1. Investigate the elastic collision for two cases: a) equal mass spheres, and b) unequal mass spheres.

2. Investigate the nonelastic collision for two cases: a) equal mass spheres, and b) unequal mass spheres.

3. Write down the results in the table.

Elastic collision				
m_1	m_2	α_0	α	β
Nonelastic collision				
m_1	m_2	α_0	γ	

4. Estimate the errors connected with your measurements and verify the equations (1) and (2) for equal and unequal mass spheres.

The estimation of the errors for elestic collision may be done by following procedure.

If $A = m_1 \sin\frac{\alpha_0}{2}$ and $B = m_2 \sin\frac{\beta}{2} + m_1 \sin\frac{\alpha}{2}$ (sigh “+” we have choosen as we find the maximum possible error), then $\Delta A = m_1 \cdot \frac{1}{2}\cos\frac{\alpha_0}{2} \cdot \Delta\alpha_0$, and

$$\Delta B = m_1 \cdot \frac{1}{2}\cos\frac{\alpha}{2} \cdot \Delta\alpha + m_2 \cdot \frac{1}{2}\cos\frac{\beta}{2} \cdot \Delta\beta \simeq \frac{\Delta\alpha}{2}\left(m_1 \cdot \cos\frac{\alpha}{2} + m_2 \cdot \cos\frac{\beta}{2}\right),$$

where $\Delta\alpha = \Delta\beta = 10' = 0,01\,\text{rad}$ is the error of the angle determination. As the maximum possible error is equal to the error of measurement of the left part of the equation B (connected with the determination of the angles for moving spheres), we believe that the absolute error of our experiment $\delta \cong \Delta B$. Therefore, the law of conservation of linear momentum is valid if $A - B \le \delta$.

The errors for inelestic collision may be determined by the similar procedure.

5. Make the conclusions as for realization of the law of conservation of linear momentum.

ELECTRICITY AND MAGNETISM

Laboratory 6 (10-E)

INVESTIGATION OF THE USEFUL POWER AND EFFICIENCY OF THE VOLTAGE SOURCE

Purpose:

To investigate the theoretical dependence of the useful power and efficiency of the voltage source on the load resistance and the current in circuit.

Theory:

The net power of the voltage source is

$$P = I^2 R + I^2 r = P_u + P_d = \mathrm{E} I \,,$$

where I is the current, R is the load resistance, r is the internal resistance of the source, E is its emf, P_u is the useful power and P_d is the power dissipated in the source.

The efficiency of the source is

$$\eta = \frac{P_u}{P} = \frac{U}{\mathrm{E}} = \frac{1}{1 + \frac{r}{R}} \,,$$

where R is the potential drop across the load resistance.

According to Ohm's Law

$$I = \frac{\mathrm{E}}{R + r} \,.$$

Then the useful power is

$$P_u = I^2 R = \frac{\mathrm{E}^2 R}{\left(R + r\right)^2} \,.$$

The useful power is equal to zero in two cases: 1) when $R = 0$ (short circuit) and 2) when $R = \infty$ (open circuit).

The extremum of the $P_u = f\left(R\right)$ function is observed when $R = r$, consequently, the maximum of the useful power is $\left(P_u\right)_{\max} = \frac{\mathrm{E}^2}{4r}$. The efficiency of the source in this case is 50% and this is not favorable. The efficiency is equal to 100% when the circuit is open, but P_u is equal to zero in this case. So the requirements of simultaneous reception of the maximal useful power at the maximal efficiency are impracticable.

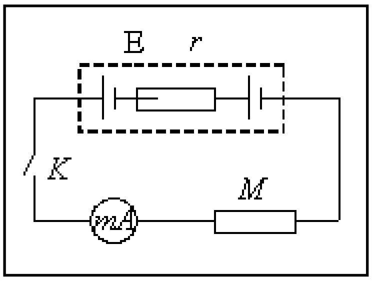
Usually the increase of efficiency is achieved by reduction of internal resistance of a source.

Materials:

Voltage source, resistance box, miliammeter, connecting wires.

Procedure:

1. Construct the experimental circuit: connect ammeter and resistance box to the voltage source in series.



2. Measure the current for the different resistances.
3. Calculate the useful power $P_u = I^2 R$ and the efficiency

$$\eta = \frac{1}{1 + \frac{r}{R}}.$$

4. Write down the results in the table

R, Ω	I, A	I^2, A^2	R_u, Ω	R, Ω	η

4. Make two plots: P_u (R) and η (R).
5. Make the summery about the effective usage of the voltage source.

Laboratory 7 (11-E)

KIRCHHOFF'S RULES FOR CIRCUITS

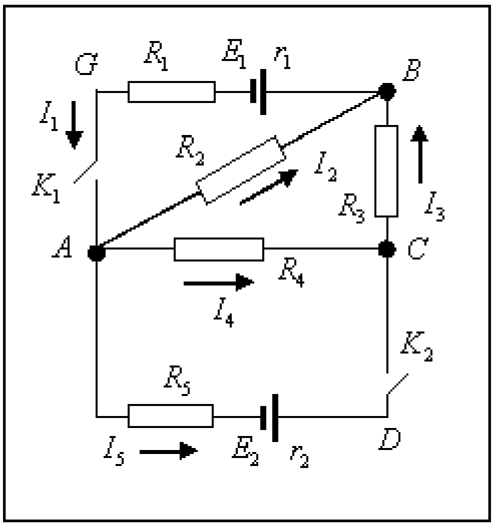
Purpose:

To test the reliability of Kirchhoff's rules for electric circuits.

Theory:

Complicated circuits cannot be reduced to a series circuit or a parallel circuit. One cannot find equivalent resistances using the rules from resistors in series or in parallel. Instead, Kirchhoff's Current and Voltage Laws are used to solve these circuits.

1. *Kirchhoff's Current Law.* This fundamental law results from the conservation of charge. It applies to a *junction* (or *node*) in a circuit is a point in the circuit where charge has several possible paths to travel. Once charge has entered into the node, it has no place to go except to leave (this is known as conservation of charge). The total charge flowing *into* a node must be the same as the total charge flowing *out of* the node. Then, the sum of all the currents is zero. This can be generalized as follows $\sum_{i=1}^{k} I_i = 0$.



Note the convention we have chosen here: current flowing *into* the node is taken to be negative, and currents flowing *out of* the node are positive. It should not really matter which you choose to be the positive or negative current, as long as you stay consistent.

2. *Kirchhoff's Voltage Law.* Kirchhoff's Voltage Law (or Kirchhoff's Loop Rule) is a result of the electrostatic field being conservative. It states that the total voltage around a closed loop must be zero. If this were not the case, then when we travel around a closed loop, the voltages would be indefinite. Therefore,

$$\sum_{i=1}^{k} U_i = 0 \quad \text{or} \quad \sum_{i=1}^{k} I_i R_i = \sum_{i=1}^{n} E_i ,$$

where the algebraic sum of potential drops is equal the algebraic sum of emf in any closed loop.

Materials:

5 resistors (of different value), voltmeter, 2 voltage sources, 2 connecting wires.

Procedure:

1. Prepare the table for experimental data.

R, Ω	U, V	I, A	E_1, V	E_2, V

2. Measure the emf E_1 and E_2.

3. Close the switches K_1 and K_2. Measure the voltage drops across each resistor. Find the direction of the current in them taking into account the arrangement of "+" and "-"of voltmeter.

4. Show the current direction at the electric scheme. Calculate the currents using the Ohm's Law.

5. Check the Kirchhoff's Current Law for each node of the experimental circuit.

6. Check the Kirchhoff's Voltage Law of closed loops of the experimental circuit.

7. Estimate the measurement errors taking into account accuracy rating of voltmeter.

For example, for node B

$$\sum \Delta\left(\frac{U}{R}\right) = \frac{R_1\Delta U_1 + U_1\Delta R_1}{R_1^2} + \frac{R_2\Delta U_2 + U_2\Delta R_2}{R_2^2} + \frac{R_3\Delta U_3 + U_3\Delta R_3}{R_3^2} .$$

Error of the resistance measuring is equal to the unit of the last significant digit of the number of the magnitude of the resistance.

8. Make the conclusions about the validity of Kirchhoff's rules.

Laboratory 8 (12-E)

CALIBRATION OF GALVANOMETER AND DETERMINATION OF ITS CHARACTERISTICS

Purpose:

To make the calibration of moving-coil galvanometer and to define its main characteristics.

Theory:

Galvanometer is the basic constituent part of a voltmeter, ammeter, or ohmmeter. Mechanical galvanometers are made from a coil of wire and a magnet. Magnetic field is created by the permanent magnet. Iron cylindrical core is located coaxially with the cylindrical surface of pole pieces. The coil may rotate in the magnetic field of the radial configuration which is in the pole gap. The angle of the coil turn is proportional to the torque which acts on the coil during the current goes through the galvanometer. They respond linearly to small currents. Hence the permanent-magnet moving-coil galvanometer has the evenly divided (uniform) scale.

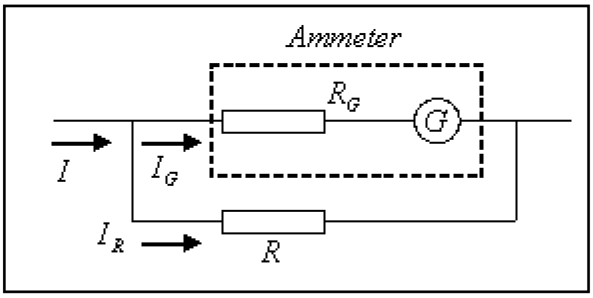
Calibration of the galvanometer includes:

1. Determination of measurement limits;
2. Determination of its scale factor and sensitivity;
3. Determination of the internal resistance of galvanometer.

The different types of meters are constructed from a galvanometer and properly placed resistors.

For example, the galvanometer may work as ammeter and as voltmeter. Moreover, the shunts and series resistors are used for the expansion of limits of measurements.

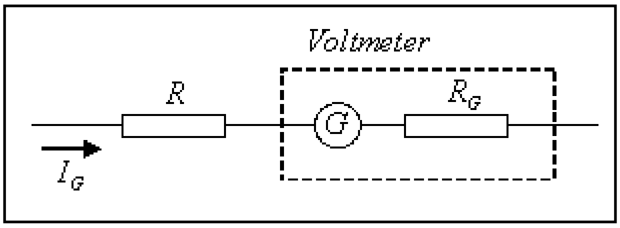
a) A galvanometer of internal resistance R_G reads full scale when I_G passes through it. We need to use it for measurements of current I, which is greater then I_G. If the entire I goes through the galvanometer, it will blow up. We must provide an alternate path for the current. We can control the fraction of the current that goes through the galvanometer with a resistor called a "shunt". Using the junction theorem, $I = I_G + I_R$. The loop theorem requires $I_G R_G - I_R R = 0$. Solving for I_R and substituting into junction theorem equation,



$$I_R = \frac{R_G}{R} I_G \quad \Rightarrow \quad I = I_G \left(1 + \frac{R_G}{R}\right) \quad \Rightarrow \quad R = \frac{R_G}{(I/I_G) - 1} = \frac{R_G}{k-1},$$

where $k = \frac{I}{I_G}$ is the shunt coefficient.

b) We may use the identical galvanometer to build a voltmeter to measure up to voltage *U*. If the entire voltage across the galvanometer is *U*, the current will be huge and galvanometer will be spoiled. We must cut down the voltage across the galvanometer by connecting it with resistor in series. Using the loop theorem, $U = I_G R_G + I_G R$.



Solving for *R*, $R = \frac{U}{I_G} - R_G$.

Materials:

Galvanometer, resistance box, voltage source, resistor (shunt), connecting wires.

Procedure:

1. Construct the experimental circuit: connect galvanometer and resistance box to the voltage source.

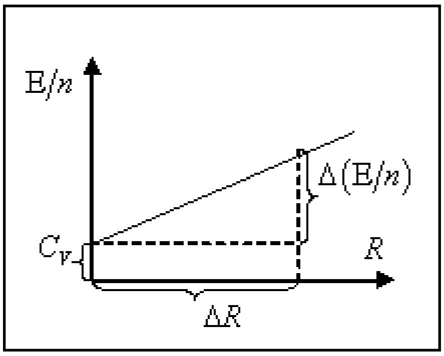
2. Choose the magnitudes of resistance to place the pointer at the integer amount n of scale divisions (the magnitudes must be in the second half of the scale).

3. Make the measurements for 5 magnitudes of resistance. Write dowm the results of measurements in the teble.

R, Ω	R', Ω	n, div	E, V	E/n, V/div	R_{sh}, Ω	R_G, Ω

4. Make the plot of dependence $\mathrm{E}/n = f(R)$, where E is the emf of the cell.

5. Find the scale factor of galvanometer using as ammeter C_A and the scale factor of galvanometer using as voltmeter C_V.



According to Ohm's law $\mathrm{E} = I(R + R_G)$, where I is the current in the circuit. Divide each part of this equation by n and obtain $\frac{\mathrm{E}}{n} = \frac{I}{n}(R + R_G)$. As $\frac{I}{n} = C_A$, then $\frac{\mathrm{E}}{n} = C_A(R + R_G)$.

The expression $\frac{\mathrm{E}}{n} = C_A R + C_A R_G$ is the equation of a straight line, where C_A is slope coefficient (it is equal to tangent of slope angle) and $C_A R_G = C_V$ is equal to the section of the axes of ordinates which is cut by the line $\mathrm{E}/n = f(R)$.

6. Find the internal resistance of galvanometer by shunt method.

Connect the shunt of known resistance R_{sh} in parallel to galvanometer. Choose the magnitudes of resistances R' to place the pointer at the same integer amounts n of scale divisions as in step 2. Find the internal resistance $R_G = \frac{R_{sh}(R - R')}{R'}$.

7. Find the sensitivities of the galvanometer using as ammeter and voltmeter

$$S_A = \frac{n}{I} = \frac{1}{C_A} \quad \text{and} \quad S_V = \frac{n}{U} = \frac{1}{C_V}.$$

8. Determine the limits of measurement for galvanometer using as ammeter and voltmeter

$$U_{\max} = n_{\max} C_V \quad \text{and} \quad I_{\max} = n_{\max} C_A.$$

9. Find the difference between the limits of measurement without and with the shunt. Describe it in summary.

10. Estimate the measurement errors.

Laboratory 9 (16-1-E)

MEASUREMENT OF THE EARTH'S MAGNETIC FIELD BY MEANS OF TANGENT GALVANOMETER

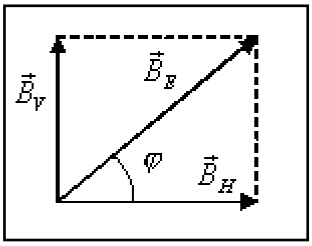
Purpose:

To investigate the magnetic field of the Earth by means of measurement of the horizontal component of the Earth's magnetic field $\vec{B}_H$.

Theory:

The Earth's magnetic field resembles that of a huge bar magnet; however, the interior temperature of the Earth is above the Curie temperature for ferromagnetic materials and a bar magnet would lose its magnetism. The Earth's magnetic field must be related to motion or currents within its core.

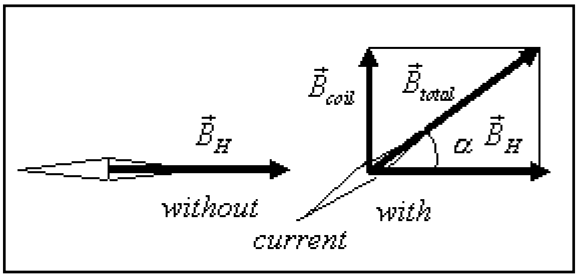
Navigators have used the Earth's field for centuries. Compass needles are light bar magnets which align themselves with the Earth's field when they are free to rotate. By long tradition, the end of the compass needle which points north is called the North Pole. But since opposite poles attract, it must be a magnetic south pole that is closest to the Earth's geographic North Pole (the magnetic poles of the Earth do not coincide exactly with the geographic poles). The Earth's field varies from place to place and therefore must be determined experimentally. In general, the magnetic field lines $\vec{B}_E$ enter the Earth's surface at an angle and so can be resolved into horizontal $\vec{B}_H$ and vertical $\vec{B}_V$ components, as shown in the following figure drawn in a vertical plane. The dip angle (φ) can be measured with a compass in such a vertical plane.



A *tangent galvanometer* can be used to measure small uniform magnetic fields such as the Earth's. It consists of *N* turns of wire around a ring of radius *R* in a vertical plane. If a current *I* is passed through the coil then a horizontal magnetic field is created at the center of the ring with magnitude

$$B_{coil} = \frac{\mu_0 IN}{2R}$$

If the tangent galvanometer is oriented so the Earth's magnetic field vector is in the plane of the coil then the field created by the coil will be perpendicular to the Earth's field vector $\vec{B}_E$ and, obviously, its two components $\vec{B}_H$ and $\vec{B}_V$. Then the compass will point in the direction of the vector sum of $\vec{B}_H$ and $\vec{B}_{coil}$, as shown in the following diagram which is drawn in a horizontal plane. From the diagram it is easy to see how the tangent galvanometer got its name.



$$\mathrm{tg}\alpha = \frac{B_{coil}}{B_H} = \frac{\mu_0 IN}{2RB_H}.$$

Therefore,

$$B_H = \frac{\mu_0 IN}{2R \cdot \mathrm{tg}a},$$

where I is the current in the coil, N is the amount of the coil turns,

R is the turn radius, $\mu_0 = 4\pi \cdot 10^7 \frac{H}{m}$.

Materials:

Tangent galvanometer, ammeter, rheostat, direct current source, to-from current switch.

Procedure:

1. Hook up the tangent galvanometer (and an ammeter in series) to a low voltage, high current power supply. Also adjust the tangent galvanometer so the compass platform is level.

2. Orient the tangent galvanometer so the Earth's magnetic field vector is in the plane of the coil; then rotate the compass dial until the needle indicates north.

Current direction 1				Current direction 2			
I, A	α	tgα	B_H	I, A	α	tgα	B_H
$\overline{B}_H$				$\overline{B}_H$			
$\overline{B}_H$							

3. Note the compass needle deflection α for various values of I. Change the current direction.

4. Write down the results of measurments in the table and find the horizontal component of the Earth's magnetic field B_H.

5. Estimate the errors of measurments and make the conclusions.

Laboratory 10 (16-2-E)

DETERMINATION OF THE MAGNETIC DIP ANGLE BY MEANS OF THE FIELD STRUCTURE AND BALLISTIC GALVANOMETER

Purpose:

To determine the magnetic dip angle φ.

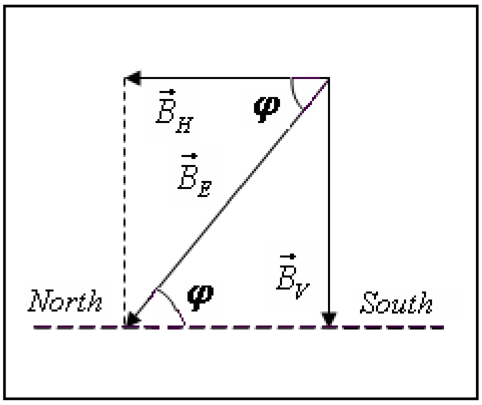
Theory:

The vector of the Earth's magnetic field $\vec{B}_E$ in the specific place of the Earth makes the angle φ (magnetic dip angle) with the horizontal plane. This angle is determined be the following equation

$$\mathrm{tg}\varphi = \frac{B_V}{B_H}.$$

The phenomenon of electromagnetic induction may be used for determination of this parameter. According to the Faraday's Law the motional emf E_i is equal to

$$\mathrm{E}_i = -\frac{d\Phi}{dt}.$$



If the plane frame consisting of N turns rotates in the uniform magnetic field, the induction current I is generated in it:

$$I = -N\frac{d\Phi}{R \cdot dt},$$

where R is the total resistance of the circuit.

Taking into account that $I = \frac{dq}{dt}$, the charge q in the frame is

$$q = \int_0^t I\,dt = -\frac{N}{R}\int_{+\Phi_{\max}}^{-\Phi_{\min}} d\Phi = \frac{2N\Phi_{\max}}{R},$$

where $+\Phi_{\max}$ and $-\Phi_{\max}$ are the magnitudes of the magnetic flux through the plane of the frame in its initial and final positions.

If we place the axis of the frame horizontally in the magnetic meridian plane, then at its rotation by 180º the turns cross the vertical component of the Earth's magnetic field and the charge induced in the frame is

$$q_1 = \frac{2NB_V S}{R},$$

where S is the area of the frame.

This charge is registered by ballistic galvanometer which pointer deflects by n_1 divisions.

If the axis of the frame rotation is placed vertically and the frame is perpendicular to the horizontal component of the Earth's magnetic field, the rotation by 180º causes the deflection of the galvanometer pointer n_2 due to the charge q_2 flowing in the frame:

$$q_2 = \frac{2NB_H S}{R}.$$

Dividing q_1 by q_2 and taking into account that $q_1/q_2 = n_1/n_2$, we obtain

$$\mathrm{tg}\varphi = \frac{B_V}{B_H} = \frac{n_1}{n_2}.$$

Materials:

Field structure (the plane round frame consisting of *N* turns of radius *R* which can rotate around the axis passing through its diameter), compass, and ballistic galvanometer.

Procedure:

1. Connect the ballistic galvanometer to the field structure.
2. Install the axis of frame rotation horizontally in the plane of the Earth's magnetic meridian. The frame of field structure has to be in horizontal plane (normally to the vertical component of the Earth's magnetic field $\vec{B}_V$).
3. Rotate the frame by 180º and write down the galvanometer pointer deflection n_1.
4. Repeat this procedure 5 times and find the mean magnitude of $\langle n_1 \rangle$.
5. Install the axis of frame rotation vertically in the plane of the Earth's magnetic meridian. The frame of field structure has to be in vertical plane normally to the horizontal component of Earth's magnetic field $\vec{B}_H$.
6. Rotate the frame by 180º and write down the galvanometer pointer deflection $\langle n_2 \rangle$.
7. Repeat this procedure 5 times and find the mean magnitude of n_2.
8. Calculate the tangent of magnetic dip angle $\mathrm{tg}\varphi = \dfrac{\langle n_1 \rangle}{\langle n_2 \rangle}$
9. Estimate the errors of experiment and make the conclusions.

OPTICS

Laboratory 11 (1-O)

DETERMINATION OF DAMPING DECREMENT OF TUNING FORK DAMPED OSCILLATIONS

Purpose:

To determine the damping decrement of damped oscillations of tuning fork.

Theory:

Tuning fork (tonometer) is the acoustical instrument characterizing by the strictly definite frequency of its own oscillations.

The motion of any object of mass m oscillating in the dissipating medium is described according to Newton's 2nd law by

$$m\ddot{x} = -kx - r\dot{x},$$

where r is the coefficient of friction (resistance of medium), and k is the coefficient of quasielastic force.

Reduce this equation to the following form

$$\ddot{x} + 2\beta\dot{x} + \omega_0^2 x = 0,$$

where $\beta = r/2m$ is the *damping coefficient*, and $\omega_0 = \sqrt{k/m}$ is the natural (own) frequency, i.e., the frequency of the system without friction. This motion equation may be solved in the form:

$$x = A_0 e^{-\beta t}\cos(\omega t + \alpha),$$

This is the *equation of free damped oscillations.* The effect, called *damping*, will cause the vibrations to decay exponentially unless energy is pumped into the system to replace the loss.

The amplitude of damped oscillations varies under the exponential law $A(t) = A_0 e^{-\beta t}$.

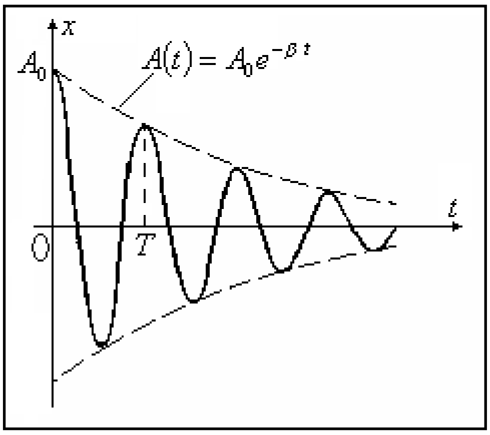
Angular frequency of damped oscillations is

$$\omega = \sqrt{\omega_0^2 - \beta^2}\ .$$

Conditional period of damped oscillations is

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

Damping decrement is the quantity equaled to the ratio of the amplitudes corresponding to the instants of time distinguished by the period, i.e.,



$$D = \frac{A(t)}{A(t+T)} = \frac{A_0 e^{-\beta\, t}}{A_0 e^{-\beta(t+T)}} = e^{\beta\, T}\ .$$

Logarithmic damping decrement (damping factor) is

$$\delta = \ln D = \beta T\ .$$

The determination of the damping decrement may be made by measurement of the period of time for the amplitude falling off twice. This time is determined by means of stopwatch by observing the oscillations of the mark drawn on the plate rigidly fastened at one of the tines of the tuning fork.

The observations are carried out by means of microscope supplied by the scale located in the eyeglass.

If the amplitude has decreased twice for the period of time $\tau = NT$, where N is the number of oscillations, then

$$\frac{A_0}{A_\tau} = \frac{A_0}{A_0 e^{-\beta\tau}} = e^{\beta\tau} = e^{\beta NT} = \left(e^{\beta T}\right)^N = 2\ .$$

Consequently, $D = e^{\beta\, T} = \sqrt[N]{2}$.

The number of oscillations can be calculated as $N = \frac{\tau}{T} = \nu \cdot \tau$, where ν is the natural frequency of tuning fork.

Practically the relationship $\sqrt[N]{2} \cong 1 + \frac{\ln 2}{\nu\tau}$ is used. Hence, the damping decrement is

$$D = 1 + \frac{0,693}{\nu \cdot \tau}.$$

Materials:

The tuning fork, the optical microscope, the stop watch.

Procedure:

1. Measure the period of time τ for the amplitude falling off twice.

2. Calculate the damping decrement finding out the magnitude of tuning fork frequency at the installation.

3. Determine the logarithmic damping decrement δ.

3. Estimate the errors and make the conclusion.

Laboratory 12 (2-O)

DETERMINATION OF THE SOUND SPEED IN METAL

Purpose:

To determine the speed of sound in metal by means of acoustic resonance.

Theory:

The speed of sound in metal can be calculate using the relationship

$$v = \lambda \cdot \nu ,$$

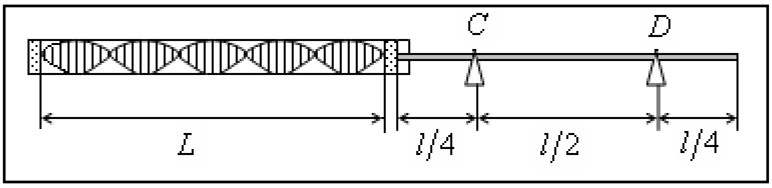
where λ is the wavelength of sound in metal and ν is its frequency.

Magnitudes of λ and ν are determined by means of Kundt's installation. This device consists of the glass tube with tightly closed one end. The metallic rod with cork disc is inserted into another end of tube. The rod is fixed at the points C and D.

Rubbing the middle part of the rod by the cloth powdered by common resin we can excite the longitudinal standing wave in the rod the nodes of which are at the fixed points of the rod. The wavelength is equal to the rod length $\lambda = l$.

The determination of the frequency ν is carried out by means of resonance of the air in the tube.

The oscillations of the cork disc initiate the periodic extensions and compressions of the air in the tube. If the air pile resonates with the oscillations of the rod, the frequency ν is equal to the frequency of the sound wave in the air ν_0:



$$\nu = \nu_0 = \frac{v_0}{\lambda_0},$$

where $v_0 = 331\sqrt{1+0,00367t}$ m/s is the speed of sound in the air at the temperature t (^{0}C), and λ_0 is the sound speed in the air.

Consequently, the speed of sound in the metal v is

$$v = l\,\frac{331\sqrt{1+0,00367t}}{\lambda_0}.$$

The magnitude of λ is determined by means of the crushed cork located in the glass tube. The standing wave in the tube scatters the crushed cork forming so call Kundt’s figures. Measuring the number of the figures N and the length of the tube L we can find the wavelength in air

$$\lambda_0 = \frac{2L}{N} \;.$$

Hence, the speed of sound in the metal is

$$v = \frac{l \cdot N}{2L} 331\sqrt{1+0,00367t}\;.$$

Materials:

Kundt’s installation, ruler, thermometer, cloth, common resin.

Procedure:

1. Rub the rod by the cloth to initiate the standing wave in the tube.
2. Measure the length of the tube and the number of the Kundt’s figures.
3. Determine the speed of sound in the metal.
4. Estimate the errors and make the conclusions.

Laboratory 13 (3-O)

DETERMINATION OF SOUND SPEED BY MEANS OF THE OSCILLOSCOPE AND SOUND GENERATOR

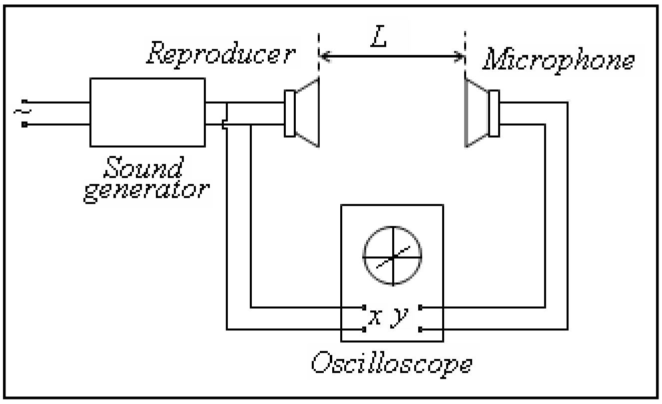
Purpose:

To determine the sound speed in the air by means of the oscilloscope and sound generator.

Theory:

The determination of the sound speed in this experiment is based on the measurement of the frequency shift of the sound oscillations applied to the plates of the electron beam tube of oscilloscope.

The operating principle of oscilloscope is that the electron beam goes through two sets of plates (or magnetic coils) - one horizontal and one vertical.



Both of them operate independently. The horizontal set of plates is connected to the sound generator, which generates the sine sound wave applied to the reproducer. The sinusoidal signal makes the electron beam moving continuously from left to right. The vertical set of plates is connected to an external signal converted by the microphone located on the optic bench at a distance from the reproducer. The phase shift of two voltages with the equal frequencies depends on the distance L between the reproducer and the microphone, on the sound speed in the air where the sound wave propagates, and on the sound frequency ν.

As the harmonic electric oscillations of the same frequency are applied to the horizontal and vertical sets of plates, the electron beam takes part in two oscillations at right angle.

When two simple harmonic oscillations

$$\begin{cases} x = A\cos(\omega_0 t + \varphi_1) \\ y = B\cos(\omega_0 t + \varphi_2) \end{cases}$$

superimpose, the resultant trajectory of electron beam is ellipse:

$$\frac{x^2}{A^2} + \frac{y^2}{B^2} - \frac{2xy}{AB}\cos\Delta\varphi = \sin^2\Delta\varphi,$$

where $\Delta\varphi = \varphi_1 - \varphi_2$ is the initial phases difference.

In dependence on the initial phases difference $\Delta\varphi$ there are three special cases:

1. $\Delta\varphi = 0$ (or $\pm 2\pi n$). Resulting motion occurs along a straight line $y = (B/A)x$ with a frequency ω_0 and the amplitude equaled to $\sqrt{A^2 + B^2}$.

2. $\Delta\varphi = \pm\pi$ (or $(2n+1)\pi$). Resulting motion takes place along a straight line $y = -(B/A)x$ with frequency ω_0 and the amplitude equaled to $\sqrt{A^2 + B^2}$.

3. $\Delta\varphi = \pm\pi/2$ (or $(2n+1)\frac{\pi}{2}$). The trajectory of resulting motion is an ellipse reduced to the principal axes, which equation is

$$\frac{x^2}{A^2} + \frac{y^2}{B^2} = 1.$$

The phase difference

$$\Delta\varphi = 2\pi\frac{L}{\lambda} = \frac{2\pi L\nu}{v_s},$$

where v_s is the sound speed in the air.

Materials:

Oscilloscope, sound generator, reproducer and microphone located on the optic bench, thermometer.

Procedure:

1. Switch on the sound generator and set a certain sound frequency ν.

2. Switch on the oscilloscope beforehand connected it to the reproducer and microphone.

3. Choose the position of the microphone to observe the straight line on the screen of oscilloscope. The phase shift in this case is $\Delta\varphi = \pm 2\pi n$.

4. Displace the microphone away from the reproducer to observe the straight line on the screen of oscilloscope again. In is understandable that the displacement $\Delta L = \lambda$.

5. Displacing the microphone obtain the straight line for the several times (n). Using these data find the mean magnitude of λ: $\lambda = \Delta L = \dfrac{L}{n}$.

6. Find the velocity of sound in the air at room temperature as $v_s = \lambda \nu$.

7. Find the velocity of sound v_0 at 0^0C according to $v_s = v_0\sqrt{1 + 0,004 \cdot t^0 C}$.

8. Estimate the errors and make the conclusions.

Laboratory 14 (8-O)

STANDING ELECTROMAGNETIC WAVES IN TWO-WIRED LINE

Purpose:

To measure the dielectric permittivity ε of the water by comparison of the wavelengths in two-wired lines located in the air and in the water.

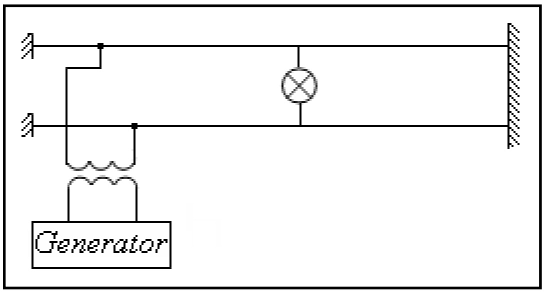
Theory:

If the generator of electromagnetic oscillations has been coupled inductively with two long wires, the traveling electromagnetic (EM) waves are in them. The electric line directs the EM waves along the wire.

If the length of line is multiple to the wavelength, the standing wave appears in the wire as a result of superposition of traveling and reflected waves. An amplitude of standing wave is different at different points of the wave. It reaches its maximum in antinodes and minimum in nodes. The distribution of antinodes of electric and magnetic fields depends on the boundary conditions.

At electrically unclosed end of the wire the magnetic field is zero as the electric current induced by EM wave is zero. Hence, there is the antinode of electric field and the node of magnetic field.

The electric oscillations induced in the two-wire line can be considered as the forced oscillations of the voltage and the current at the segment of line. If the frequency of generator approaches to one of the own frequencies of the line, the resonances of current and voltage are observed. Therefore, the electric field at antinodes is sufficiently large. If we place the indicator (neon lamp) in the region of antinode it switches on, and it switches off at nodes. Displacing the indicator along the line and marking the places where the indicator glows most brightly we can find the distance (wavelength of standing wave) which is equal to a half of the wavelength of the traveling wave.



According to Maxwell's theory the velocity of EM wave propagation is

$$v = \frac{c}{\sqrt{\varepsilon\mu}},$$

where ε is dielectric permittivity and μ is magnetic permeability of substance.

Otherwise, the velocity of EM wave is $v = \lambda\nu$, where λ is the wavelength of EM wave in substance and ν is its frequency.

In vacuum

$$c = \lambda_0\nu,$$

where λ_0 is the wavelength in vacuum.

Consequently,

$$\varepsilon = \left(\frac{\lambda_0}{\lambda}\right)^2.$$

Materials:

Two-wire lines in the air and in the water, indicator, and generator of EM waves.

Procedure:

1. Switch on the generator of EM waves.
2. Displacing the indicator along the two-wire line in the air mark the places of the brightest glow of lamp. Find the wavelength of EM wave in the air as doubled distance between antinodes.
3. Make the same procedure investigating the two-wire line in the distilled water.
4. Using the experimental data find the dielectric permittivity of distilled water.
5. Estimate the errors and make the conclusions.

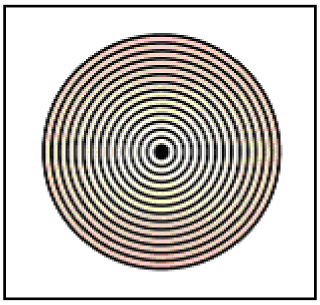
Laboratory 15 (12-O)

DETERMINATION OF CURVATURE RADIUS OF LENS AND LIGHT WAVELENGTH BY MEANS OF NEWTON'S RINGS

Purpose:

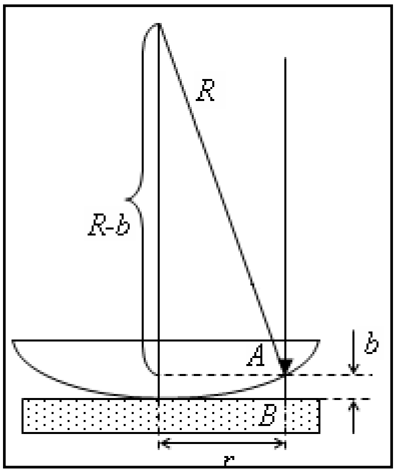
To determine the curvature radius of lens and light wavelength by means of Newton's rings.

Theory:



When a curved glass surface is placed in contact with a flat glass surface, a series of concentric rings is seen when illuminated from above by monochromatic light. These are called *Newton's rings* (fringes). They are the result of the interference of rays reflected by the top and bottom surfaces of the very thin air gap between two glass surfaces (just like a thin film). As the width of the air gap increases from the central contact point out to the edges, the extra path length for the lower ray varies, giving rise to a series of bright and dark lines.

The optical path difference between rays reflected from points separated by distance b is given by $\Delta = 2bn$, where n is the refractive index of material in clearance. Taking into account the phase change at reflection, the path difference is



$$\Delta = 2bn + \frac{\lambda}{2}.$$

From the scheme of the experiment

$$R^2 = \left(R - b\right)^2 + r^2 = R^2 - 2Rb + b^2 + r^2.$$

Neglecting a quantity b^2 since $b \ll r$ and $b \ll R$, we express b

$$b = \frac{r^2}{2R},$$

where r is the radius of Newton's ring, and R is the lens radius.

Bright fringe is the result of constructive interference:

$$\left.\begin{aligned} &\Delta + \frac{\lambda}{2} = 2k \cdot \frac{\lambda}{2} \Rightarrow \Delta = \left(2k - 1\right)\frac{\lambda}{2} \\ &\Delta = 2bn = 2\frac{r^2 \cdot n}{2R} = \left(2k - 1\right)\frac{\lambda n}{2} \end{aligned}\right\}$$

Radius of bright ring $r_k = \sqrt{\dfrac{\left(2k - 1\right)R\lambda}{2n}}$, ($k$ = 1, 2, 3 …)

Dark ring is the result of destructive interference:

$$\left.\begin{aligned} &\Delta + \frac{\lambda}{2} = \left(2k + 1\right) \cdot \frac{\lambda}{2} \Rightarrow \Delta = 2k\frac{\lambda}{2} \\ &\Delta = 2bn = 2\frac{r^2 \cdot n}{2R} = 2k\frac{\lambda n}{2} \end{aligned}\right\}$$

Radius of dark ring $r_k = \sqrt{\dfrac{kR\lambda}{n}}$, ($k$ = 0, 1, 2, 3…)

Materials:

Installation for obtaining Newton's rings.

Procedure:

1. Obtain the clear image of Newton's rings in the microscope field of view using red light $(\lambda_r \cong 0{,}62\ \mu\text{m})$.

2. Measure the diameters of Newton's rings by means of the scale located in eye-piece of microscope.

3. Using the multiplying factor of the scale find the true magnitudes of the diameters.

4. Find the radius of curvature of the lens by means of expression:

$$R = \frac{r^2}{k\lambda_r} = \frac{d^2}{4k\lambda_r},$$

where *k* is the number of the ring.
It is desirable to take rings with number greater than 4.

5. Measure the diameters of dark rings using the green light illumination.

6. Find the wavelength of green light

$$\lambda_g = \frac{r^2}{kR} = \frac{d^2}{4kR},$$

Where R is the diameter of the lens has been defined in item 4 of this lab.

7. Estimate the errors and make conclusions.

Laboratory 16 (17-O)

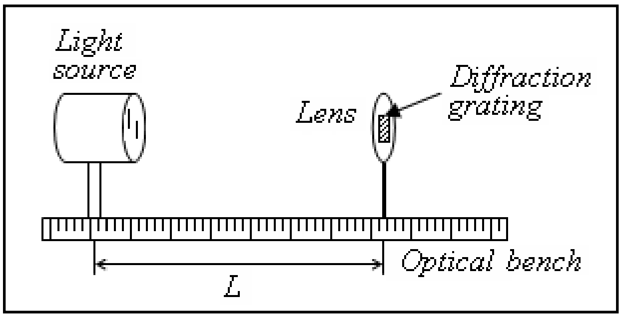
DETERMINATION OF WAVELENGTH BY MEANS OF DIFFRACTION GRATING AND DOUBLE-SLIT LIGHT SOURCE

Purpose:

To determine the light wavelength by means of the diffraction grating.

Theory:

Diffraction is the bending of radiation (such as light) around the edge of an obstacle or by a narrow aperture (of light wave-length order). Diffraction results from the interference of light. Waves that pass an opaque body produce a fuzzy region between the shadow area and the lighted area that, upon close examination, is actually a series of light and dark lines. According to the Huygens-Fresnel principle every point on a wave-front may be considered as the source of secondary spherical wavelets spread out in the forward direction at the speed of light. The new wave-front is the tangential surface to all of these secondary wavelets. These wavelets “interfere” with one another at points after the screen. This interference pattern is called a *diffraction pattern*.



A *diffraction grating* is the object with a large number of parallel, closely spaced slits. It is the spectral device which allows separating light of different wavelengths with high resolution. If b is a slit width and a is an opaque gap width, $d = a + b$ is a *grating constant*.

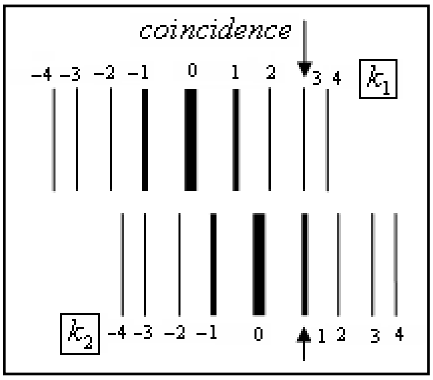
Let plane wave incident on grating at the angle *i*. Converging lens focuses light to the screen. Image on the screen is result of diffraction and interference. Each slit produces a diffraction pattern and the diffracted beams then interfere with each other to produce the final pattern.

Each slit acts as a source and all sources are in phase. At some arbitrary direction away from horizontal, the beams must travel different path lengths to arrive at screen.

If the path-length difference is equal to one wavelength or an integer number of wavelengths then bright line (constructive interference) is observed at screen. Therefore, the condition for maximum at the angle ψ_k is

$$d\left(\sin i + \sin\psi_k\right) = \pm k\lambda,$$

where ψ_k is diffraction angle, and k is the number of diffraction maximum.



Hence $\lambda = \dfrac{d\left(\sin i \pm \sin\psi_k\right)}{k}$.

If we use two incoherent sources of light the diffraction pattern is two systems of maxima displaced relatively each other. The positions of the diffraction maxima systems depend on the distance between the light source and diffraction grating L. Writing down the diffraction maximum conditions for both slits and jointly solving the equations we can obtain the expression which allows finding the light wavelength:

$$\lambda = \frac{d \cdot l}{L\left(k_1 + k_2\right)},$$

where d is grating constant, l is the distance between slits, k_1, k_2 are the numbers of conterminous diffraction maxima.

Materials:

Double-slit source of light, diffraction grating and lens located on the optical bench.

Procedure:

1. Obtain the diffraction patterns from each of two sources.

2. Displacing the diffraction grating along the optical bench achieve the coincidence of the diffraction maxima of k_1 and k_2 numbers.

3. Calculate the wavelength.

4. Repeat this procedure for the several times calculating the wavelength for each position.

5. Find the mean magnitude of the wavelength, estimate errors and make the conclusion.

Laboratory 17 (25-O)

INVESTIGATION OF BLACKBODY RADIATION

Purpose:

To investigate the thermal radiation laws and the optical pyrometer operation, to determine the Stefan-Boltzmann constant.

Theory:

Thermal radiation is the electromagnetic radiation emitted by heated bodies due to their internal energy. It depends only on the temperature and the optic properties of these bodies.

The intensity of thermal radiation is characterized by the energy flux, emitted by unit area of the body surface along all directions - *radiant emittance* $R_{\omega T}$ (the total energy radiated per square meter per second at a temperature T or the rate at which radiation is emitted from a unit area):

$$dR_{\omega T} = r_{\omega T} d\omega ,$$

where $r_{\omega T}$ is the *emissive (radiating) power*.

As the radiation consists of the waves of different frequencies ω, therefore,

$$R_{\omega T} = \int dR_{\omega T} = \int_0^{\infty} r_{\omega T} d\omega .$$

The *absorption coefficient* (absorptivity) $a_{\omega T}$ is the ratio of the absorbed (Φ_{ab}) and incident (Φ_{in}) fluxes of energy.

$$a_{\omega T} = \frac{d\Phi_{ab}}{d\Phi_{in}} .$$

Absorptivity $a_{\omega T}$ is the function of frequency and temperature.

A black body absorbs all the radiation it receives (nothing is reflected). Mathematically, a black body is defined to have $a_{\omega T} \equiv 1$ at any temperature.

The Stefan-Boltzmann law states that the total energy emitted by the blackbody per unit area per second - radiant emittance - is

$$R^* = \sigma T^4 ,$$

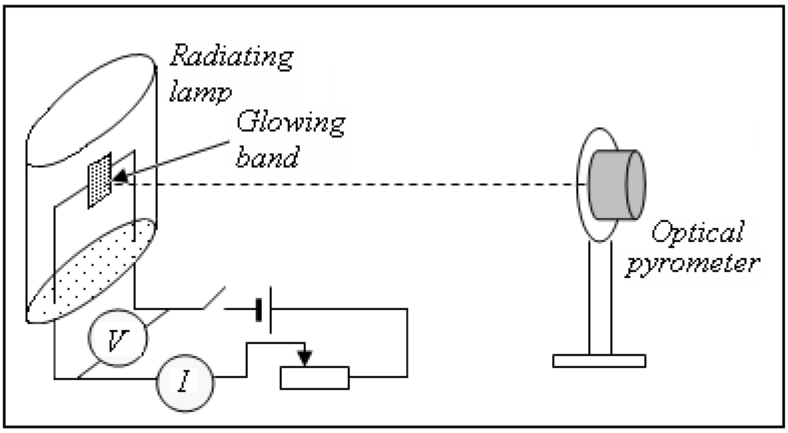
where $\sigma = 5{,}67 \cdot 10^{-8} \dfrac{\text{W}}{\text{m}^2 \cdot \text{K}^4}$ is the Stefan-Boltzmann constant.

If the radiation takes place at the temperature T_0 the radiant emittance is equal to

$$R^* = \sigma \left(T^4 - T_0^4 \right).$$

Wein's displacement law: the wavelength λ_m of maximum radiance of a blackbody depend on the temperature $\lambda_m = \dfrac{b}{T}$, where $b = 2{,}898 \cdot 10^{-3}\,\text{m} \cdot \text{K}$ is the Wein's constant.

Pyrometry is the set of noncontact methods of temperature measurements. The appropriate devices are called the *pyrometers*. Optical pyrometer consists of the



optical components that collect the radiant energy emitted by the target object, a radiation detector that converts the radiant energy into an electrical signal, and an indicator that provides readout of the measurement. It requires manual adjustment based on what is viewed through a sighting window. Because it relies on what can be seen by the human eye, optical pyrometer is designed to respond to very narrow band of wavelengths that fall within the visible light portion of the electromagnetic spectrum. The brightness optical *pyrometer with disappearing filament* detects a balance in brightness between a lamp filament and the object of measurement in a narrow visible wavelength passband.

The lamp with nichrome band is used as the radiating unit in this experiment. Nichrome band is heated by electric current. The current power $P = IU$ spent for the maintenance the band at a given temperature compensates the power that is radiated. Hence, $IU = \sigma S\left(T^4 - T_0^4\right)$, where S is the area of glowing part of the band, I and U are the current and the voltage, T is the temperature of the glowing part of the lamp, and T_0 is the room temperature.

Consequently, the Stefan-Boltzmann constant is

$$\sigma = \frac{IU}{S\left(T^4 - T_0^4\right)}.$$

Materials:

Optical pyrometer with disappearing filament, ammeter, voltmeter, rheostat, radiating unit (nichrome band), thermometer.

Procedure:

1. Switch on the experimental electrical circuit.
2. Using rheostat adjust recommended magnitudes of current *I*.
3. Observing the glowing band through the eye-piece of the pyrometer, turn the adjuster to make the filament of pyrometer invisible on the background of the glowing band.
4. Write down the results of measurements in the table.

I, A	U, V	S, m^2	T, K	T_0, K	σ, W·m^{-2}·K^4

5. Find the Stefan-Boltzmann constant.

6. Repeat the procedure for different temperatures of glow (changing the current I).

7. Estimate the errors and make the conclusion.

ATOMIC AND NUCLEAR PHYSICS

Laboratory 18 (1-A)

INVESTIGATION OF DISCRETE SPECTRA

Purpose:

To investigate the visible parts of hydrogen and helium spectra and comparison the experimental results and theoretical calculations according to Balmer formula.

Theory:

Hydrogen spectrum consists of the sets of lines in ultraviolet, visible and infrared regions. Discreet spectrum connected with the quantization of energy of electron in atom. Wavelengths are described by Balmer formula:

$$\frac{1}{\lambda} = R \cdot \left(\frac{1}{n_i^2} - \frac{1}{n_k^2} \right),$$

where $R = 1{,}1 \cdot 10^7\,\mathrm{m}^{-1}$ is the Rydberg constant (for wavelength).

For visible part of spectrum $n_i = 2,\ n_k = 3, 4, 5...$

For hydrogen-like ions the wavelengths of spectrum lines are:

$$\frac{1}{\lambda} = Z^2 R \cdot \left(\frac{1}{n_i^2} - \frac{1}{n_k^2} \right),$$

where Z is the number of element in Periodic Table.

Materials:

Separate tubes of hydrogen and helium (or another gas) whose spectra are available. High voltage (a few kV) power supplies for electric discharging of the gases. The tubes should already be connected to the power supplies. Spectroscopes (with slits) to view emission spectra.

Procedure:

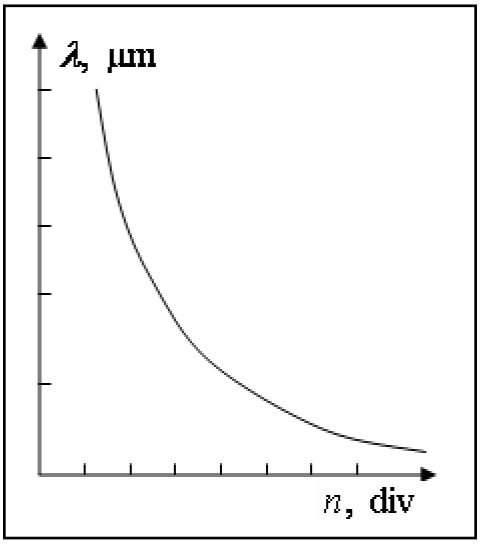
1. Turn on the power supply that holds the helium tube. After the tube "lights up" you can observe the emission spectrum of helium through the spectroscope. First look into the scope directly at the slit and then rotate the spectroscope until you see light directly passing through the slit into your eye.

2. Observe the emission spectra for helium. Sketch the emission spectrum and label each line in terms of (approximate) color and the number of divisions using the spectroscope scale.

3. Write down the results in the table.

n, div	color	λ, m

3. Using the reference data plot the calibration curve of spectroscope - $\lambda(N)$, where λ is the wavelength and n is the number of divisions.



4. Turn off the supply. Put the hydrogen tube and repeat the procedure. Using the calibration curve find the wavelengths of hydrogen spectrum.

5. Calculate the theoretical magnitudes of wavelengths of hydrogen using the Balmer formula and compare them with experimental results.

6. Estimate the errors and make the conclusions.

Laboratory 19 (2-A)

FRANK-HERTZ EFFECT

Purpose:

To investigate the discrete character of changing energy of atoms by means of Frank-Hertz effect.

Theory:

According to Bohr’s theory the transition of the electron from one energetic state to another is accompanied by the energy emission

$$\Delta E_{ik} = E_i - E_k\,,$$

where E_i, E_k are the energies of atoms in two states.

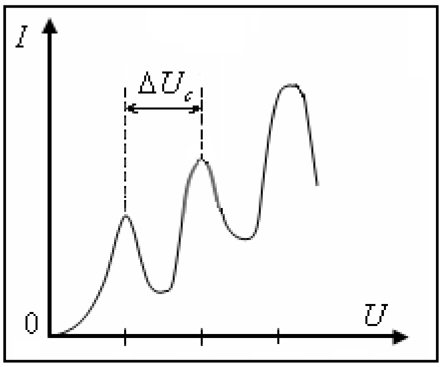
The frequency of emitted or absorbed energy is

$$\nu_{ik} = \frac{\Delta E_{ik}}{h},$$

where $h = 6,62 \cdot 10^{-34}\,\text{J} \cdot \text{s}$ is Planck’s constant.

In the Frank-Hertz experiments the interaction of electrons accelerated by the electric field with the gas atoms was investigated. These interactions are of two types: elastic and inelastic.

At the elastic collisions of the electrons and atoms only the direction of the electron velocity changes, and its magnitude is practically the same. Hence there isn’t any energy transmission.



At inelastic collisions the electrons transit their energies to atoms, hence the atoms change their energetic states, as the result, the electrons lose their velocities.

The type of collisions depends on the energy of electron which depends on the accelerating potential difference (p.d).

At a certain magnitude of p.d. the electron begins to collide inelestically (the first critical excitation potential U_c or resonance potential). If the atom is in the ground state (E_0) before the collision then after the collision it transfers in the first exited state (E_1). Practically immediately the atom returns to the ground state emitting the photon with energy $\varepsilon = h\nu_1$, where ν_1 is the resonance frequency. According to the law of conservation of energy

$$\Delta E_{01} = E_1 - E_0 = eU_c = h\nu_1 = h\frac{c}{\lambda_1}.$$

At the greater magnitudes of accelerating p.d. the electron transfers the energy which is sufficient for the transitions to other exited states.

The Frank-Hertz effect was the first direct proof of quantization of atomic levels and generally the postulates of Bohr’s theory.

Materials:

Thin gas filled triode, ammeter, voltmeter, potentiometers, and voltage source.

Procedure:

1. Switch on the experimental installation.
2. Changing the voltage U read the magnitude of the current I writing them down into the table.

I, A	U, V	ΔU, V	ΔE_{01}, V	ν, Hz	λ, m

3. Plot the dependence $I(U)$ on linear graph paper and find experimentally the potential difference between two peaks of the curve line ΔU.
4. Calculated the corresponded magnitude of ΔE_{01}.

5. Using experimental data find the frequency

$$\nu_1 = \frac{\Delta E_{01}}{h} = \frac{e\Delta U}{h}$$

and the wavelength

$$\lambda_1 = \frac{c}{\nu_1}$$

of resonance line and compare them with the reference data.

6. Estimate the errors and make the conclusion.

Laboratory 20 (6-A)

DETERMINATION OF DE BROGLIE WAVELENGTH BY MEANS OF ELECTRON DIFFRACTION PATTERNS

Purpose:

To determine de Broglie wavelength of electrons by means of electron diffraction patterns obtain in electron microscope.

Theory:

Louis de Broglie in 1924 suggested that particle, such as electron and protons, should exhibit wavelike properties. The wavelike nature of matter was based on a conviction that nature is inherently symmetric. De Broglie based on the connection between particle and wave properties from the Einstein-Planck expression for the energy of electromagnetic wave

$$E = h\nu = \hbar\omega = \frac{hc}{\lambda}$$

and the classical result for linear momentum of such a wave

$$p = \frac{E}{c} = \frac{h\nu}{c} = \frac{h}{\lambda}.$$

Therefore,

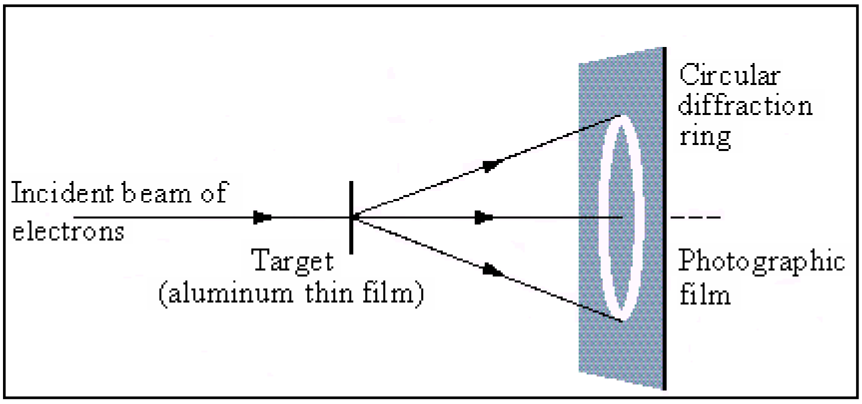
$$\lambda = \frac{2\pi\hbar}{p} = \frac{h}{p},$$

where $\hbar, h$ are Planck's constants; p is the linear momentum of the particle (for classical particle - $p = mv$ and for relativistic particle - $p = mv \Big/ \sqrt{1-(v/c)^2}$, where m is the rest mass, v is the velocity; $c = 3 \cdot 10^8$ m/s is the light speed in vacuum).

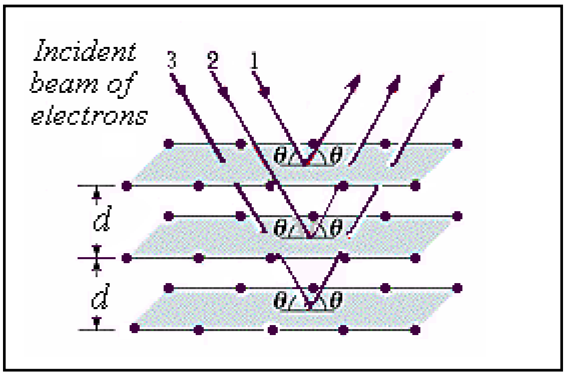
When a monochromatic light beam is incident on an ordinary ruled diffraction grating, a clearly defined pattern appears on a distant screen, where the maxima are given by:

$$\sin\psi = \frac{k\lambda}{d},$$

where d is the grating spacing (grating constant), ψ is the angle between the direction of the incident beam and the direction from the grating to the location of the maximum (diffraction angle), and k = 0,1,2,3,… is the spectral order. The interference observed is a clear indication of the wave effect.



Within crystalline solids the atoms exist in a regular lattice structure. Planes of regularly spaced atoms within these structures, referred to as Bragg planes, can reflect waves and these waves can also produce interference patterns.



It can be shown that the condition for constructive interference of these waves which are reflected from the parallel Bragg planes is:

$$2d_{hkl}\sin\vartheta = m\lambda,$$

where m = 1, 2, 3, ... is the order of the reflection, d_{hkl} is the spacing between the adjacent parallel lattice planes, λ is de Broglie wavelength of electrons and ϑ is the angle between the incident and reflected beams and the lattice planes. This is known as Bragg's law.

For the calculation of the electron diffraction patterns obtained by means of electron microscope Bragg's law is

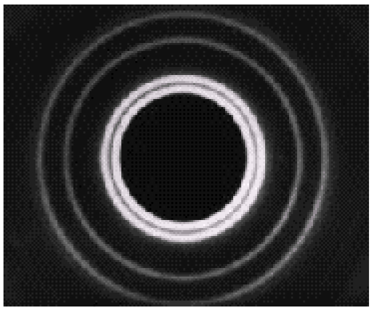
$$d_{hkl}\cdot D = 2mL\cdot\lambda,$$

where D is the diameter of circle at electron diffraction pattern and L is characteristics of the electron microscope (equalled to the distance from the object to the photographic film).

An electron accelerated from rest through a potential difference of U volts acquires kinetic energy

$$eU = \frac{mv^2}{2} = \frac{p^2}{2m},$$

where $p = mv$, and the electron's kinetic energy is sufficiently small (much smaller than the rest energy of the electron) so that relativistic effects may be neglected.



It follows then that

$$\frac{p^2}{2m} = \frac{h^2}{2m\lambda^2}$$

or

$$\lambda = \frac{h}{\sqrt{2meU}}.$$

In relativistic case

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2m_0eU\left(1+\frac{eU}{2m_0c^2}\right)}},$$

where m_0 and e are the rest mass and the charge of electron.

Materials:

Electron diffraction patterns, the ruler.

Procedure:

1. Measure the diameters of circles at the electron diffraction patterns.
2. Calculate the de Broglie wavelengths using the reference data ($d_{hkl}, L, m = 1)$.
3. Find the theoretical magnitudes of the de Broglie wavelengths at a given *U*.
4. Compare experimental and theoretical magnitudes. Estimate errors and make the conclusions.

Laboratory 21 (14-A)

INVESTIGATION OF PHOTOCONDUCTIVITY KINETICS

Purpose:

To determine the life-time of nonequilibrium carriers of charge in semiconductors.

Theory:

Nonequilibrium carriers of charge stipulate the operation of important semiconductor devices: triodes, diodes, thermal resistors, photoresistors, etc.

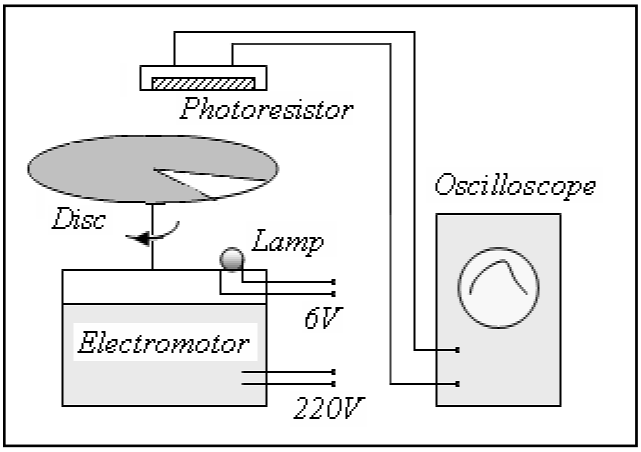
If free carriers of current are formed as a result of thermal ionization of semiconductor, the temperature of the crystal lattice and electrons is the same. The carriers which concentration is corresponded to thermal equilibrium are the equilibrium carriers. Under the excitation by light nonequilibrium carriers are formed.

In the semiconductor under illumination the number of nonequilibrium carriers formed per unit time in unit volume is proportional to the light intensity I:

$$\Delta n = \beta k I; \quad \Delta p = \beta k I,$$

where $\Delta n, \Delta p$ are the numbers of nonequilibrium electrons and holes, k is the absorbtion coefficient, β is the quantum output (the number of "electron-hole" pairs initiated by one photon).

Additional conductivity of semiconductor initiated by illumination is photoconductivity. Without recombination the conductivity of semiconductors should increase. But in practice both generation of nonequilibrium carriers and their recombination take place. Hence, after a short period of time the stationary concentration of nonequilibrium carriers is mounted.



This property stipulates the time lag of photoresistors.

The concentration of the carriers under the illumination change according to

$$n = n_0 \left(1 - e^{-\frac{t}{\tau}}\right),$$

where n_0 is the stationary concentration and τ is the life-time of nonequilibrium carriers of charge.

When illumination is ceased the concentration of charge carriers decreases as

$$n = n_0 e^{-\frac{t}{\tau}}.$$

Photocurrent is

$$I = ebnES,$$

where e is the charge of electron, b is carrier mobility, E is the electric field strength, S is the cross-section of semiconductor.

Therefore, the law of photocurrent relaxation $(t \to \infty)$ at the illumination of the semiconductor is

$$I = I_0\left(1 - e^{-\frac{t}{\tau}}\right).$$

The law of photocurrent relaxation at darkening of the semiconductor is

$$I = I_0 e^{-\frac{t}{\tau}}.$$

The time-life τ may be determined if we know the time Δt of the 10% decreasing the photocurrent:

$$0,9I_0 = I_0 e^{-\frac{\Delta t}{\tau}},$$

then

$$1,1 = e^{-\frac{\Delta t}{\tau}}$$

and

$$\tau = \frac{\Delta t}{\ln 1,1}.$$

If the disc turns at the frequency *n*, the darkening time is

$$t_0 = \frac{1}{n}.$$

Materials:

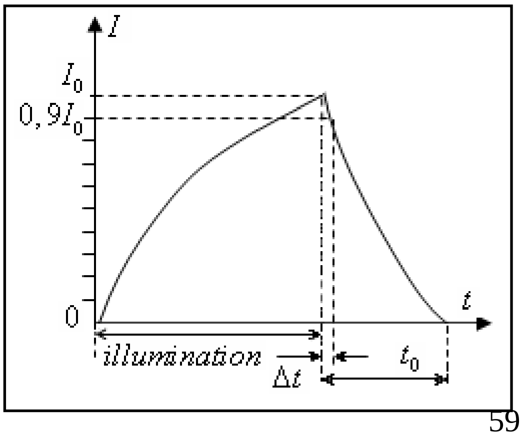
Experimental installation with disc-modulator, oscilloscope, photoresistor.

Procedure:

1. Sketch the curve from the oscilloscope screen using the tracing-paper.

2. Find the multiplying factor of oscilloscope scale by comparison of the darkening time found from the sketch and by calculation according the formula.

3. Find the time Δt experimentally.



4. Determine the life-time τ.
5. Estimate the errors and make the conclusions.

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