Synopsis of General Physics Laboratory at MIPT

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You can get much further with a kind word and a gun than you can with a kind word alone.

Alphonse Gabriel "Al" Capone

Rephrasing Al Capone, a researcher who relies both on experiment and theory will advance much further than a researcher who relies on theory alone. It would be absolutely wrong to think that experiment serves only to verify a certain model, – very often experimental discoveries initiate new fields of research.

However, not all experiments are destined to be revolutionary. Reality is more complicated than any physical model, so a good experiment is the one which emphasizes the phenomenon under study and reduces the background "noise". Textbook problems - we used to solve in school and at the University - already suggest the parameters which could be neglected, the real life is, unfortunately, not that simple. An experiment must be carefully planned, thought through, and designed so that the phenomenon under study to become prominent. A good experiment makes physics of the studied effect transparent and understandable, even without the use of complicated models. In other words, a principle: "if a nut doesn't crack - take a bigger hammer" is not for a good experimentalist; a talented physicist is able not only to find the right wrench to unscrew a tough nut but he will also measure the thread lead and handedness, friction coefficient, and many other parameters.

The history of physics knows a number of remarkable experiments, some of them are presented in this book. This laboratory course by itself makes a good treatise of general physics, no offense to the brilliant textbooks by D.V.Sivukhin. Incidentally, study of physics from the experimental viewpoint allows one to have a different and often deeper understanding of the same phenomenon. Moreover, some of the experiments are really masterpieces and can be used over and over again to study new physical systems.

We do research because we enjoy discovering phenomena which nobody could find before. A good experiment can be compared to sneaking in nature's boudoir while a mediocre one gives access only to an entrance hall. From my own experience, I would add to "Al Capone theory" that a combination of a gun and a kind word must be a source of fun for you and produce surprising results •

Konstantin Novoselov,
Nobel laureate 2010,
MIPT 1997

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The booklet contains short descriptions of physics labs performed by MIPT students as a part of general physics course.

For physics instructors and the students pursuing BS degree in physics.

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Preface

This booklet contains short descriptions of physics labs performed by MIPT students as a part of general physics course. It consists of six semester courses: mechanics, thermodynamics and molecular physics, electricity and magnetism, optics, and quantum micro- and macro-physics. Usually there are 8–10 lab sessions per semester. Working in the laboratory is a cornerstone of the general physics course. Also the curriculum includes lectures and extensive problem solving sessions.

Nobel laureate academician Peotr Leonidovich Kapitza, one of the MIPT founders (1951), always emphasized the special role of practicum in teaching physics. P.L. Kapitza has laid the main principles of MIPT education known as "principles of fiztekh": 1) search and selection of gifted and inclined to creative work students; 2) study and work under supervision of leading researchers; 3) mentoring students to develop their creativity and avoid passive learning; 4) applying the acquired skills to real projects in the best research laboratories of the country.

The laboratory course was developed by hundreds of experienced physicists working in MIPT. The most notable contribution was made by A. I. Shalnikov, G. S. Landsberg, K. A. Rogozinskii, V. E. Skorovarov, G. S. Gorelik, N. E. Alekseevskii, and L. L. Goldin. Now the course includes the best labs designed for the last 60 years.

Among the faculty of the General Physics Department at MIPT were the following members of the Russian Academy of Science: P. L. Kapitza, L. D. Landau, Yu. V. Sharvin, R. Z. Sagdeev, L. P. Pitaevskii, N. V. Karlov, I. F. Schegolev, S. M. Rytov, and I. L. Fabelinskii. Professor D. V. Sivukhin, the author of a well-known five-volume "Course of General Physics", worked at the Department for many years. Professor S. M. Kozel, a member of the organizing committee of the International Olympiad in Physics, is now one of the favored physics lecturers at MIPT.

Currently there are about 200 faculty members including 30 Doktor nauk (the highest post-graduate degree) and 70 Kandidat nauk (equivalent of PhD). About one half of the faculty are researchers working at the institutes of Russian Academy of Science, such as the Lebedev Physical Institute, the Prokhorov General Physics Institute, Institute of Solid State Physics, and also government funded research centers such as the Kurchatov Institute. Other faculty members are experienced physics lecturers.

The labs included in the booklet teach students to handle physical devices thereby developing practical understanding of physics. Many MIPT graduates successfully use this knowledge in their research in Russia and abroad. Two of them, Konstantin Novoselov and Andre Geim were awarded the Nobel prize in 2010 for novel experiments with a two-dimensional material graphene.

I. Mechanics

1. Determination of systematic and random errors in measurement of specific resistance of nichrome

A measurement of the resistance of a nichrome wire is used to introduce the concept of systematic error. At first the resistance is determined by measuring the current through the wire and the voltage across it. The method gives a rough result since the internal resistances of the instruments are not taken into account. A direct determination of the wire resistance that makes use of a Wheatstone bridge allows students to reach a better accuracy. The difference between the values obtained by two methods is then compared with a theoretical estimate of the error of the indirect measurement. Finally students measure the dimensions of the wire and determine the specific resistance of nichrome which is compared with the standard value.

2. Measurement of linear expansion coefficient of a rod with the aid of microscope

A linear expansion coefficient of a metal rod is measured in the lab. The rod is placed in an electric oven encased in a steel pipe. The rod temperature is measured by a resistance thermometer connected to a Wheatstone bridge. A quartz tube with a mark on it is clasped at one end of the rod. A microscope is focused on the mark. Rod lengthening is registered by the mark displacement observed in the microscope. The linear expansion coefficient is determined by plotting mark displacement vs. thermometer resistance on a chart. The coefficient is proportional to the slope of the curve. In the lab students improve their measurement skills and get acquainted with the graphical method of data treatment.

3. Statistical treatment of measurements

The purpose of the lab is to introduce the concept of random error by studying stochastic deviations of the actual resistance from the resistor face value. To determine the resistance a digital voltmeter is used whose accuracy is much smaller than a typical deviation of the resistance. Using the measured values of a large pool of resistors the mean value and the standard deviation are calculated (the mean value is then compared to the face value). The whole range of the measured resistances is divided into equal intervals and a histogram of probability density is plotted. A dependence of the histogram shape on sampling is then examined. Finally students draw the Gaussian distribution curve using the calculated mean value and the standard deviation.

4. Measurement of radiation background intensity

Statistical laws are studied by registering cosmic rays by means of a Geiger–Muller counter. A random variable in this case is a number of particles detected during a definite time interval (count time). Students examine an influence of the total number of measurements (duration of experiment) on a mean value, a mean value fluctuation, on a fluctuation of a single measurement, and on the standard deviation. A histogram of the probability density of counts is plotted. A dependence of the histogram shape on the duration of count time is examined. Then students plot the Gaussian and Poisson distribution functions using the mean value and the standard deviation determined. These curves approximate histograms for different values of count time.

5. Study of elastic proton-electron collisions

The lab is aimed at studying elastic collisions between electrons and protons. Specifically the dependence of the angle between outgoing electron and proton on the momentum of δ-electron is analyzed. Students examine the photos of particle tracks taken in a bubble chamber placed in a uniform magnetic field. They select a δ-electron track and measure the angle and the initial curvature radius of the electron trajectory. The electron momentum is then deduced from the curvature. The obtained dependence of the angle cosine on the electron momentum is compared with the theoretical prediction derived by a graphical method. The comparison allows students to decide whether nonrelativistic formulae are applicable in this case. Finally the initial momentum of the protons is calculated.

6. Study of electronic oscilloscope

The design, the principle of operation, and the operating modes of an oscilloscope are studied. Low frequency generators supply sinusoidal and rectangular shaped pulses to the oscilloscope input channels. Students learn how to handle the oscilloscope and to measure the signal frequency and amplitude. They calibrate the generator attenuator and determine the sensitivity, the gain frequency characteristics, and the phase frequency characteristics of x and y channels. The next task is to study the influence of the gain frequency characteristics on the rectangular pulse distortion. Finally various Lissajous figures are observed in the $x-y$ mode.

7. Determination of bullet velocity by means of ballistic pendulum

The bullet velocity is measured by detecting the result of its collision with a massive gravity pendulum. The duration of a bullet collision with the pendulum is negligible compared to the oscillation period of the latter. Therefore the laws of momentum and angular momentum conservation can be applied. By measuring the pendulum oscillation amplitude and using the law of conservation of energy students determine the bullet momentum and therefore its velocity. The lab consists of two parts.

a. Method of ballistic pendulum

A massive cylinder is suspended on four threads so that its axis is horizontal. Students fire a shot at the cylinder along its axis. A transparent ruler is attached to the lower part of the cylinder. A beam of light passing through the ruler is reflected by a mirror and the ruler image is observed on an opaque screen. Students find a screen location that enables to measure the oscillation amplitude with a better accuracy.

b. Method of ballistic torsional pendulum

A metal rod with two small targets is fastened to a rigid vertical wire. Students shoot at one of the targets. A small mirror with a vertical mark on its surface is attached to the rod center. The mirror is illuminated so that the mark image is reflected on an opaque ruler. By registering the motion of the image along the ruler one can measure the amplitude of torsional oscillations.

8. Determination of inertia moments of rigid bodies by means of trifilar torsion suspension

The main objective of the lab is to determine experimentally the inertia moments of different bodies (a slab, solid and thin-walled cylinders) by measuring the oscillation period of a trifilar torsion suspension loaded with a body.

The trifilar torsion suspension is the main element of the laboratory setup; it is a metal disc suspended on a cantilever with three long threads attached at three periphery points of the disc. Obviously the oscillation period of such a system depends on its moment of inertia with respect to the rotational axis and the technique of measuring the moments of inertia of rigid bodies is based on this observation. The oscillation period is measured by means of a photo-detecting counter.

Besides the primary task (measuring the moments of inertia) students verify experimentally Huygens-Steiner theorem: they measure the variation of the suspension oscillation period caused by displacement of the load away from the rotation axis.

A nice feature of the lab is a very good agreement between the experimental values of the moments of inertia and the values obtained by straightforward calculations provided the measurements are carefully done.

9. Determination of principal moments of inertia of rigid bodies by means of torsional oscillations

By studying physical principles of mechanics the first-year physics majors get some primary knowledge about inertia tensor and inertia ellipsoid which are the basic concepts of the rigid body dynamics. Theoretical mechanics provides a method of determination of the inertia ellipsoid for a given rigid body. For such bodies as cube and parallelepiped the relations between the principal axes of the inertia ellipsoids are simply expressed via the lengths of their edges. The lab is aimed to determine the components of inertia tensor of these bodies experimentally, to plot their inertia ellipsoids, and to compare the data obtained with the theoretical predictions.

To determine a moment of inertia of a body students fasten it to a sliding frame which is suspended by two tight threads fastened to its upper and lower sides and then measure the period of its torsional oscillations.

A body (a cube or a rectangular slab) can be fastened to the frame in various positions. The frame axis can coincide with a body's edge, its main diagonal, or its face diagonal. The corresponding oscillation period turns out to be proportional to the square root of the moment of inertia, this fact helps to plot the inertia ellipsoid accurately enough.

This lab provides a helpful visualization of the complicated problem of rigid body dynamics.

10. Study of gyroscope precession

The lab concerning study of a gyroscope is one of the most important in the course of rigid body dynamics. At first students get entertained by an unconventional response of the gyroscope to a force applied to it but mainly the lab is aimed to describe the phenomenon quantitatively.

The main element of the laboratory setup is the gyroscope rotor in a Cardan suspension. The spinning of the rotor is due to an alternating voltage supplied by an external source whose frequency is measured in the lab. One can observe a fast precession of the gyroscope about the vertical, which starts when a load is suspended on the gyroscope axis. The precession speed depends on the load mass. Besides one can notice a slow precession caused by friction in the bearings. By determining the dependence of the precession angular velocity on the load mass students estimate the angular momentum and rotation frequency of the gyroscope and the torque due to the friction force in the bearings.

An additional part of the lab is a measurement of the signal of emf generated in the rotor windings by means of an oscilloscope. These measurements provide a possibility of crosschecking the value of the rotation frequency obtained before. The observation of the emf signal generated when the external voltage is turned off allows one to determine the mechanical Q-factor of the gyroscope.

11. Determination of Young's modulus based on measurements of tensile and bending strain

In a high school physics curriculum Hooke's law is demonstrated by means of an ordinary spring. An observation of deformations of solid bodies is a complicated problem since these deformations are really small. In the lab Hooke's law is verified by measuring a uniaxial tension of a steel wire and bending tension of beams made of different materials.

By measuring the uniaxial tension students obtain the dependence of the wire extension on the load mass. An experimental setup consists of a wire suspended on a metal cantilever. A platform for the loads is attached to the lower end of the wire. The wire extension is detected by a light beam deflected from a mirror which is non-rigidly attached to the wire. Having obtained the experimental data set students determine Young's modulus of the wire material and estimate the range of extensions where Hooke's law is valid.

The bending of the beams vs. the load mass is measured by means of a micrometric indicator. Just as in the first part of the lab Young's modulus of different materials (wood, steel, brass) is estimated by the dependence of the bending deflection on the load mass. However the calculations in this case are more complicated. Moreover students observe that the measurement results are sensitive to the position of the point where the the load is placed.

In addition to the main task students estimate the influence of deformations of the setup structural elements on the measurement accuracy and become familiar with some methods of their elimination. By treating the experimental data students get some basic skills in calculating deformations of complex structures.

12. Measurement of torsional rigidity

The angular torsion of metal rods with circular cross-section is studied in the lab. The dependence of torsion angle vs external torque is measured and by fitting the experimental points to a straight line the torsional rigidity of the studied rod is then calculated.

The torsion angles are small, which complicates the measurement. To circumvent the problem two methods are used.

When using a static method the measurement of the torsion angle is done by means of an optical system. A small mirror is set directly on the rod, so that even a minor rotation of the mirror results in a noticeable displacement of the deflected light beam.

Using a dynamical method students measure the period of torsional oscillations of a rod. To determine the torsional rigidity in this case the moment of inertia of the rod must be known which in fact cannot be accurately measured.

Having processed the experimental data students compare the errors of two methods and decide which one is preferable.

13. Determination of air viscosity by measuring the rate of gas flow in thin pipes

The objectives of the lab are

- acquaintance with different regimes of gas flow, namely, laminar and turbulent;
- verification of the Poiseuille equation;
- determination of air viscosity and the Reynolds number.

The laboratory equipment consists of a set of metallic pipes of different length and diameter and a compressor which forces the air to flow through the pipes. The air flow rate is measured by a mechanical flow meter, while the gas pressure in the pipe section is determined by means of a hydrostatic manometer. Several equidistant outlets with plugs in the pipe walls serve to measure the pressure gradient along the pipes.

Connecting the manometer to different sections of a pipe, one can

- ◇ study the dependence of the flow rate vs. pressure gradient and verify the Poiseuille equation;
- ◇ estimate the range of the stationary flow formation.

Analyzing a non-linear part of the dependence of the flow rate vs. pressure gradient is of particular interest in the lab; it gives the students some basic insight into the phenomenon of turbulence.

14. Study of stationary flow of liquid through pipe

The problem of determination of the rate of stationary flow of liquid is a classical one for hydrodynamics. A theoretical estimation of the liquid velocity is provided by Torricelli's law while for the actual measurements Pito and Venturi flow meters are used. The main objective of the lab is to compare the flow meters' readings with the predictions based on Torricelli's law and to analyze applicability of the latter. The laboratory equipment consists of a tank in which the level of water can be measured and a horizontal metallic pipe protruding from the tank near the bottom. The flow meters are mounted directly on the pipe. Pouring water from a faucet at a constant flow rate into the tank students maintain a constant water level in it and measure the velocity of a stationary flow in the pipe.

Probably the most interesting part of the lab is a treatment of the experimental data. The main point here is that the dependence of the flow rate vs. the height of the liquid column can be processed using two completely different approaches: the Torricelli's (ideal liquids) and the Poiseuille's (viscous liquids). Which of the two is actually applied is the key issue of the lab.

15. Study of oscillations of physical pendulum

The purpose of the lab is to study a physical pendulum, a rigid rod with a movable pivot. Students measure the dependence of the oscillation period vs. the pendulum moment of inertia and determine the free fall acceleration by fitting the data using the least-square method.

At first sight the experimental part of the lab seems rather simple, but to obtain a meaningful data students must

- ◇ know the basics of the theory of small-amplitude oscillations;
- ◇ be able to estimate the range of its applicability.

The amplitude range where the oscillations can be considered small is determined experimentally; the effect of damping on the oscillation period is also studied. Some fundamentals of the rigid body dynamics, namely, that the pivot point and center of oscillations are interchangeable, are verified experimentally.

Usually having processed the experimental data most of the students arrive at the conclusion that the free fall acceleration cannot be determined with a sufficient accuracy by this method and offer their own ideas concerning improvement of the experimental technique.

16. Measurement of the free fall acceleration using Kater's pendulum

Since high school students get familiar with a problem of measuring the free fall acceleration g with the aid of pendulums of different types. Anyone who did such a measurement by means of a mathematical or a physical pendulum knows that it's not easy to determine g with a sufficient accuracy. The main obstacle is that the pendulum's moment of inertia cannot be measured accurately enough.

Kater's pendulum (a reversible pendulum) was the first instrument that enabled to determine g with the accuracy of 10^{-3} cm^2/s. The pendulum operation principle is based on the fact that the pivot point and the center of oscillations of a pendulum are interchangeable and so it is possible to eliminate the moment of inertia from the ultimate formula used for evaluating g. Kater's pendulum is a steel bar with two pivot points (the upper and the lower ones), its oscillation period can be varied by moving a load along the bar. The uncertainty of the value of g is extremely sensitive to the position of the movable load relative to the pivot points; this dependence is first studied theoretically and then verified experimentally.

The sensitivity of Kater's pendulum is sufficient enough to detect iron ore deposits. When students are informed about this fact an accurate determination of g becomes a real challenge for them!

17. Study of nonlinear oscillations of long-period pendulum

The lab is aimed to examine pendulum oscillations in detail. The dependence of oscillation period on the damping and on the deviations from linearity is analyzed; the lab is of particular interest from both theoretical and experimental points of view.

The pendulum oscillation period must be as long as possible to detect the effects mentioned. A special pendulum design is used for this purpose, namely, a steel rod whose center of inertia is close to the rotation axis.

The laboratory equipment gives two possibilities to determine the oscillation period. The measurement can be performed either manually (using a stopwatch) or automatically (which is preferable). In the automatic regime a light-sensitive element detects the crossing of a light beam by the pendulum rod. The detector transfers its signal to an ADC converter and the data is displayed on the computer screen.

By doing the lab students get familiar not only with the basics of nonlinear oscillations, but also obtain primary knowledge concerning systems of automatic data acquisition.

18. Study of oscillations of coupled pendulums

Oscillations of systems with more than one degree of freedom are a subject of analytical mechanics. Nevertheless the first-year physics majors can study this phenomenon experimentally by observing coupled mathematical pendulums.

The laboratory setup consists of two mathematical pendulums suspended on an elastic metallic rope whose tension is adjustable. It is the rope that enables to transfer energy between the pendulums.

Students measure

- ◇ the periods of in-phase and counter-phase oscillations;
- ◇ the time of energy transfer to the pendulum which is initially at rest.

There is a simple and well-composed theory of the phenomenon that seems complicated at first sight. Having completed the measurements students estimate the experimental errors and compare their results with the theoretical predictions.

19. Study of string oscillations

In the lab students get familiar with elastic vibrations of a string with the clamped ends. The objective of the lab is to determine the propagation velocity of the oscillations and to measure the dependence of the velocity as a function of the string tension.

The main element of the laboratory setup is a string whose tension can be adjusted by suspending different loads to one of its ends. A harmonic alternating current of a small amplitude supplied by an audio-frequency generator is passed through the string; the mechanical oscillations are due to Ampere's force exerted on the string by a permanent magnet.

Students select generator frequencies suitable for visual observation of the standing mechanical waves. Then using the known values of resonant frequencies and the half-wave lengths they determine the propagation velocity of the oscillations. The lab though it is simple experimentally possesses some interesting subtleties to which students should pay attention. For example, usage of a non-harmonic (ramp-like or pulse) alternating current leads to formation of additional standing wave modes.The students also can estimate the reflection coefficient of the wave in the holdfast based on the string oscillations' amplitudes in the nodes and antinodes. The explanation of these facts however requires a deeper insight into wave physics and encourages students' interest in further study of mechanical oscillations.

II. Thermodynamics and Molecular Physics

1. Measuring the specific heat of air at constant pressure

The aim of the lab is to determine the specific heat of air by measuring an increase in temperature of a steady flow of air which is heated when passing through a glass tube. The installation consists of the glass tube with a vacuum heat-insulated shell, a heater located inside the glass tube, and a thermoelectric couple which measures the difference in the air temperatures before and after the heater. Students measure the difference in the temperatures at various levels of the heater power. The data obtained allow them to calculate the heat capacity of air at constant pressure and the rate of thermal losses in the system.

2. Determination of the C_p/C_v ratio of gas by the method of adiabatic expansion

The aim of the lab is to measure the C_p/C_v ratio of a gas by the method of adiabatic expansion. The installation consists of a glass jar equipped with a liquid column manometer and a rubber douche for pumping extra gas to increase the pressure in the jar. At first students pump a gas in the jar and measure the difference in pressure inside and outside of the jar. Then they connect the jar to the atmosphere for a short time. When the temperature comes to an equilibrium (while the jar is closed) students measure the pressure difference. The C_p/C_v ratio is evaluated from the results of the measurement. Students carry out the measurements for air and carbon dioxide. The C_p/C_v values obtained for diatomic and triatomic gases are then compared with the theoretical values.

3. Determination of C_p/C_v ratio of gas via measurement of the speed of sound

Speed of propagation of an acoustic wave in gases depends on the adiabatic index γ (C_p/C_v ratio). One of the most precise methods of determination of the adiabatic index is based on measuring the speed of sound. The installation consists of an audio-signal generator, a tube which is filled with a gas to be explored, and an oscilloscope connected to a microphone. Students measure the adiabatic index for air and carbon dioxide. Also they measure the temperature dependence of γ in the interval from room temperature to 80 °C. Then students compare the C_p/C_v ratios obtained for diatomic and triatomic gases with the theoretical values. And finally they check that the C_p/C_v ratio remains constant at different temperatures.

4. Determination of the specific heat of solids

In the lab the specific heat of solids is measured. The measurement is carried out by the usual procedure. A solid sample is put into a calorimeter. Students measure the amount of heat transferred to the sample, and the change in the sample temperature caused by the heat transfer. The sample temperature can be reliably measured by a resistance thermometer, whereas determination of the amount of heat absorbed by the sample is usually problematic. To take into account the heat losses students are recommended to measure the sample temperature as a function of time and to make an extrapolation to the room temperature. Since at the room temperature the heat losses are zero the value obtained will coincide with the heat capacity of the sample.

5. Study of thermal effects caused by elastic deformations

The laboratory setup includes a rubber band which can be stretched by a load. The band is thermally insulated and its temperature is measured by means of a thermocouple. Two experimental tasks should be carried out.

- ⋄ Students study a nonlinear dependence of the rubber band extension on the load weight at constant temperature. The dependence is then plotted on a graph in coordinates in which the plot must be linear according to an empirical formula. Then students determine Young's modulus of rubber.
- ⋄ Thermal effects accompanying rubber stretching are measured by means of the thermocouple at different band extensions. Students measure the rate of temperature decrease of the stretched rubber. Finally using the experimental data students calculate the specific heat of rubber at constant length.

6. The Joule–Thomson effect

The Joule–Thomson effect terms variation in temperature of a gas which flows slowly from a region of high pressure into a region of lower pressure providing the gas is well thermally isolated from the environment. In the lab the variation in the temperature of carbon dioxide which is slowly flowing through a porous plug inside a tube is measured. The measurements are made at three different temperatures in a range from room temperature up to 70 °C. For each of these temperatures students measure the difference in temperature caused by the Joule–Thomson effect at various pressure differences. From the dependences obtained the Joule–Thomson coefficient is then determined. Applying the van der Vaals equation to carbon dioxide students estimate the constants a, b, and the inversion temperature for this gas from the experimental data.

7. Study of interdiffusion of gases

The experimental setup consists of two glass vessels connected by a thin long pipe. At first the two vessels are evacuated by means of a vacuum pump to ∼0,1 Torr. Then one of the vessels is partially filled with air and the other one is filled with a mixture of air and helium. The lab is a study of the diffusion of helium from the second vessel to the first one. Thermal conduction sensors located in the vessels are used to detect the concentration of helium. A difference between the sensor resistances is monitored by means of a Wheatstone bridge which readings are proportional (up to the second-order term of Taylor expansion) to the difference between the helium concentrations in the vessels. The diffusion coefficient is calculated using the measured dependence of the difference between the concentrations on time. Students measure the diffusion coefficient at different pressures in the range of 40–400 Torr and then compare it with the theoretical prediction.

8. Measurement of thermal conductivity of air at different pressures

In the lab students investigate experimentally how the thermal conductivity of air depends on pressure. The installation consists of a cylindrical vessel filled with air.

A metal filament that can be heated by electric current is located along the cylinder axis. The cylinder is connected to a vacuum pump. The filament resistance is measured by means of a Kelvin double bridge, the temperature of the filament is determined via its resistance. Students measure the thermal conductivity of air at different pressures in the range from 10 Torr up to the atmospheric pressure. The dependence obtained is then compared to the theoretical one. Also the students are to estimate the magnitude of the temperature drop next to the filament surface and the spatial extent of the drop.

9. Measurement of heat conductivity of gases at atmospheric pressure

The main part of the lab setup is a long vertical copper pipe with a nickel or tungsten wire along the pipe axis. The pipe can be filled with a gas under study. The wire is heated by electric current. The current and the voltage across the wire are measured, so both the power loss and the resistance of the wire are known, which allows one to determine its temperature. The pipe temperature is held constant by a water flowing through the outer casing. Students measure the thermal conductivity of air and carbon dioxide. Before filling the pipe with a gas the pipe volume is evacuated. The dependence of the voltage across the wire on the current is measured at several values of temperature in the range from room temperature to 70 °C. For each temperature students determine the heat conductivity of the gases.

10. Measurement of heat conductivity of solids

The lab installation is a sandwich of a heater, a cooler, and two solid disk samples between them. One of them is a sample to be investigated and the second one is made of ebonite. Temperatures of the heater and the cooler are held constant by flows of hot and cold water. Thin rubber layers are used to ensure a good thermal contact between the surfaces. Temperatures on both sides of the samples are measured by means of thermocouples. Students carry out the following procedures.

- ◇ Calibration of the thermocouples.
- ◇ Verification of independence of heat conductivity on the temperature of the ebonite sample.
- ◇ Measurement of heat conductivity of several samples.
- ◇ Experimental estimate of heat leakage through the lateral surfaces of the samples and the measurement errors due to this effect.

11. Determination of viscosity of liquid by its outflow through capillary

To measure viscosity of water a Mariotte's bottle is used. A calibrated capillary outlet is close to the bottom. The pressure at the capillary input is determined by a water column whose height is equal to the vertical distance between the capillary axis and the lower end of the air inlet. Students measure the distance by means of a millimeter rule and a microscope. The capillary diameter is measured by the microscope. Students register the outflow water volume by means of a graduated cylinder and the outflow time by a stopwatch. The measurement is carried out 4–5 times at different water pressures. The dependence of the flow rate on the height of the water column is plotted on a graph. A linear function corresponds to a laminar flow which is described by the Poiseuille equation. Using the graph students determine the water viscosity. The viscosity of a glycerine water solution is measured with respect to the water viscosity by means of an Ostwald viscosimeter. Students repeat the measurement 4-5 times for each of the 10%, 20%, and 30% glycerine/water solutions.

12. Determination of activation energy of liquid via temperature dependence of its viscosity

Activation energy of a liquid is an exponent in the power law dependence of its viscosity on temperature. Therefore one can determine the activation energy of a liquid by measuring its viscosity at different temperatures. To determine the viscosity of glycerine students measure a steady velocity of small metal spheres of different diameters falling in a transparent glass vessel filled with glycerine. The glycerine temperature is controlled by a water flow between the double walls of the vessel. Students measure the velocity by means of a stopwatch and a ruler at different temperatures in the range from room temperature up to 60 °C. For each experiment the Reynolds number is calculated and the validity of Stokes' law is verified. Students plot the experimental data in the coordinates of the viscosity logarithm vs. the inverse temperature. The activation energy of glycerine is then estimated as the slope of the linear dependence obtained.

13. Study of gas diffusion through a porous medium

The experimental setup consists of two vessels connected by a pipe filled with a porous medium. After evacuation the upper vessel is filled with helium and the lower one with air. Due to diffusion of helium from the upper vessel through the porous baffler the helium concentration in the lower vessel rises. Students determine the difference between helium concentrations in the vessels by means of two sensors which measure heat conductivity of the gases inside the vessels. Time dependence of the difference in concentrations is measured by means of a stopwatch. The procedure is repeated for 3–4 initial pressures of helium in the upper vessel. For each experiment the data is plotted in the coordinates of the logarithm of He concentration difference vs time. A straight line corresponds to a simple theoretical model of diffusion. Students estimate the diffusion coefficients as the slopes of the graphs. The inverse of diffusion coefficient is then plotted as a function of pressure in order to determine the diffusion parameters. Finally students estimate the average diameter of the pores.

14. Creation and measurement of vacuum

The lab is mainly aimed to acquaint students with the basics of vacuum technique. There are two tasks.

- ◇ Measurement of the volumes of low vacuum and high vacuum parts of the installation.
- ◇ Determination of the evacuation rate in a steady regime.

The setup includes: a positive displacement pump, a glass molecular pump, an oil U-tube manometer, two thermocouple manometers for measurements at low vacuum, and an ionisation gauge for measurements at high vacuum. To determine the volumes of the installation parts students inject a certain amount of air into the previously evacuated volumes. They measure the resulting air pressure inside a volume by the oil manometer. A volume can be calculated using the Boyle-Mariotte law. When a low vacuum is created students turn on the molecular pump to create a high vacuum. By measuring the rate of the pressure fall they calculate the evacuation rate and the pump throughput. Students also measure the vacuum decrease rate in the isolated high vacuum part to estimate the leakage of the installation.

15. Study of ion pump

The aim of this lab is to study phenomena which take place in an ion pump. In such a pump atoms of gas are at first ionized and then they are accelerated by an electric field which hammers the ions into a cathode. A lamp of ionization gauge is used both as a pump and a vacuum gauge. Students measure time dependence of ionic current during evacuation. Using the measured dependence students find the total amount of molecules that could be absorbed by the collector and the amount of molecules per unit of area of the collector surface after the evacuation.

16. Measurement of osmotic pressure

In the lab properties of semipermeable membrane are studied. Semipermeable membranes allow molecules only of certain substances to pass through thereby creating osmotic pressure. To measure osmotic pressure an osmometer is used in the lab. Students measure a rate of volume change in a vessel versus the pressure difference between two vessels divided by a semipermeable membrane. By extrapolating the measured dependences to the zero speed students find the osmotic pressure. Such a procedure is carried out for solutions of different concentrations. The obtained dependence of osmotic pressure on concentration is then compared with a theoretical prediction.

17. Study of scattering of slow electrons on mercury atoms

In the lab a cross section of scattering of slow electrons on mercury atoms is measured. By slow electrons we mean those ones whose energy is insufficient to ionize the atoms. The experimental installation consists of a cathode, an anode, and a collector. The installation is located inside a cylindrical vessel which is evacuated to a pressure of 10^{-6} torr and contains a small drop of mercury. The whole setup is placed into a thermostat filled with a transformer oil. The oil temperature determines the pressure of saturated vapor of mercury. Students measure temperature dependence of the collector current. Then using the dependence obtained they determine the scattering cross section.

18. Measurement of saturated vapor pressure of refractory metal

The aim of the lab is to measure the saturated vapor pressure of a refractory metal using an indirect method. In the lab the evaporation rate of a tantalum fiber is measured, which allows one to calculate the concentration of the saturated vapor and therefore the pressure. The experiment is carried out in a high-vacuum installation. In order to achieve a pressure of 10^{-6} torr a combination of a low-vacuum displacement pump and a molecular pump is used. The tantalum fiber is placed in an evacuated chamber and the fiber is heated to a temperature of 2500 °C. The fiber temperature is determined by the power it radiates. A reduction in the fiber mass is determined by measuring its mass before and after the experiment.

19. Measurement of latent heat of evaporation

The aim of the lab is to measure the latent heat of evaporation of water by an indirect method which is based on the Clausius–Clapeyron relation. An experimental setup includes a vessel filled with water. Before filling it the vessel is evacuated, so there is only the saturated vapor above the water surface. The vessel is placed in a thermostat which allows one to change the water temperature. A vapor pressure is measured by a mercury manometer. Students measure a dependence of the saturated vapor pressure on temperature in the range from room temperature to 40–50 °C. The measurements are carried out both for increasing and decreasing temperature. The latent heat of evaporation is calculated by using the Clausius–Clapeyron relation and the measured dependence.

20. Measurement of temperature dependence of surface tension

The aim of the lab is to measure the surface tension of a liquid at different temperatures. The installation consists of a bottle filled with a liquid under study in which an air inlet (a thin metal pipe) is submerged so that it does not touch the bottom. The upper end of the inlet is open to the atmosphere. The pressure in the bottle is lowered and air bubbles come out of the inlet at a constant rate. The pressure deficit is measured with a manometer. The Young–Laplace equation is used to calculate the surface tension. At first measurements are carried out with water in order to calculate the inlet diameter (the surface tension of water is known). Then students measure temperature dependence of the surface tension of aniline in the range from room temperature to 60 °C. The measurements are carried out both for increasing and decreasing temperature.

III. Electromagnetism

1. Magnetometer

A magnetometer is a device designed for magnetic measurements, i.e. a compass or a fluxmeter. An electromagnetic magnetometer used in the lab is a coil comprising a few sequential turns in the vertical position. In the middle of the coil there is a short magnetic pointer suspended by a thread. The device includes two mirrors attached to the coil and to the pointer.

To measure the horizontal component of the Earth's magnetic field a magnetized bar, whose magnetic moment can be found by measuring a period of torsional oscillations, is placed in the coil.

The lab assignment consists of two parts. In the first part students determine the moment of inertia and the magnetic moment of the bar and calculate the horizontal component of the Earth's magnetic field by using the magnetometer response.

In the second part students determine the speed of light by measuring a pointer deviation when a certain current flows through the coil. They should compare the measurement results obtained in the SI system with the ones in the CGS. Current is a fundamental unit in the SI while in the CGS current is expressed through the capacity and the voltage of a capacitor which discharges through the coil.

2. Absolute Voltmeter

In the CGS system a unit of electric charge is defined via the major units: centimeter, gram, and second. Thus one can define the charges of electrodes and the potential difference between them by measuring the interaction force, the dimensions and the distance between the electrodes. Such measurements and the instruments for doing them are called absolute.

Ampere, a unit of current, is a fundamental unit in the SI system and a unit of electric charge is defined as ampere times second. This definition introduces a dimensional constant ε_0 called the electric constant.

In the lab an attractive force between a capacitor plates is compared to a standard weight by means of a precision scales. The experimental setup includes the scales in which one scale is replaced with a movable plate of a plane air capacitor. Students measure the attractive force between the plates as a function of the capacitor voltage. Using the results they determine the proportionality factor which relates voltage units of the CGS and the SI and determine the electric constant.

3. Phase shift in AC electric circuit

The purpose of the lab is to study oscillatory processes taking place in electric circuits. Students study the quasi-stationary electromagnetic oscillations induced in a circuit driven by an external alternating voltage. Such an oscillation is a special case of a harmonic oscillation which is defined by its amplitude and phase. In the lab these parameters are determined with the aid of an oscilloscope. The first task consists in observing how the phase shift between the current and the voltage depends on the resistance in an RC-circuit. A similar task is done for an RL-circuit. In the final part students observe how the phase shift depends on frequency in an RCL-curcuit, a realistic oscillatory circuit. The amplitude and the phase of the oscillations can be found either by the method of complex amplitudes or by the method of vector diagrams. Students are to verify experimentally the theoretical conclusions obtained by these methods.

4. Voltage resonance

The purpose of the lab is to study oscillation processes taking place in a series electric circuit. In the lab students study quasi-stationary oscillation processes in a series circuit with a non-zero reactance. Using capacitors and inductors results in a phase shift between the current and the voltage. The method of complex amplitudes is used to determine theoretically the current and voltage oscillations. In the first task students verify Ohm's law for a special case of AC circuit. To this end a wattmeter is utilized in addition to an ammeter and a voltmeter. Then students study a voltage resonance in a series RCL-circuit. The voltage resonance is detected by a relatively high increase in the inductor and capacitor voltages whereas the net voltage in the circuit remains relatively low. An inductor with a movable core is used to vary the circuit parameters, the ammeter and voltmeters are used to measure the parameters of the oscillations. The oscilloscope is employed to observe the resonance and the phase shift between the current and the voltage.

5. Current resonance

The purpose of the lab is to study oscillation processed taking place in parallel electric circuit. Processes are observed in circuit meeting the quasi-stationary condition. Students study steady-state oscillation processes in circuit, composed from two branches: RL and C. To determine parameters of oscillations theoretically the method of complex amplitudes is used. Students verify theoretical conclusions in experiment. In the circuit, used in the lab, current resonance occurs. It is detected in abrupt increase of current in elements of circuit with relatively low total current in the circuit. Inductor with movable core is used to change parameters of circuit. Ammeters and voltmeter are used to measure parameters of oscillations. To visually observe phase shift between current and voltage the oscilloscope is used.

6. Free oscillations in electric circuit

The purpose of the lab is to study transient processes taking place in electric circuit. Students study free oscillations in an RCL-circuit which are damped due to energy dissipation. The oscillations are induced in the circuit by the capacitor charged by periodical step-wise pulses. The time dependence of the voltage and current in the free oscillation regime can be obtained by solving a linear differential equation of the second order. An oscillation circuit is characterized by two important parameters: quality factor and logarithmic decrement which are responsible for the decay rate of the oscillations. Another parameter of an electrical oscillation circuit is the critical resistance, i.e. the highest possible resistance for the oscillations to occur. In the lab students observe oscillations on the oscilloscope screen. The oscilloscope inputs are the voltage across the capacitor and the voltage derivative, so the oscillation phase plane is directly displayed. Students experimentally study how the period of free oscillations depends on the capacitance, how the logarithmic decrement depends on the resistance and determine the critical resistance and the quality factor. The values determined in the experiment are then compared with the theoretical predictions.

7. Forced oscillations in electric circuit

The purpose of the lab is to study forced oscillations and transient processes taking place in an oscillation circuit. A series RCL-circuit is used in the lab. Energy is supplied to the circuit by an external source of AC voltage connected via a separating capacitor to get rid of undesirable effects related to the output impedance of the generator. The time dependence of the oscillations can be obtained by solving an inhomogeneous linear differential equation of the second order. At first students study the stationary oscillations and plot the resonance curves for two values of the resistance. Using the resonance curves they determine the quality factors. Then students supply wave trains to the circuit and observe increasing and decreasing oscillations on the oscilloscope screen. Analyzing the images they determine the logarithmic decrement and the quality factor. Students compare theoretical values of the quality factor with those obtained in two experiments. They also observe the beats arising when a slight offset of the driving frequency from the resonance takes place.

8. Study of ballistic mirror galvanometer

The purpose of the lab is to study a highly sensitive ballistic mirror galvanometer of the permanent-magnet system. In the lab the galvanometer is used to measure current and electric charge. The basic part of the galvanometer is a current loop suspended in a radial magnetic field. The loop motion is described by a linear differential equation of the second order, the equation of harmonic oscillations. The ballistic galvanometer operates in two modes: a stationary mode to measure the current and a ballistic mode to measure the charge passed through the loop. At first students determine the ballistic constant of the galvanometer, the ratio of the current to the angle of rotation of the loop, in the stationary mode. Then they determine the critical resistance of the galvanometer, which is the minimal value of the resistance for the oscillations to occur. The second task is to study the galvanometer in the ballistic mode. In this mode the critical resistance and the ballistic constant, the ratio of the charge passed through the loop to the angle of rotation of the loop in the critical regime, are determined. Finally students compare the values of critical resistance obtained in different experiments.

9. Measurement of specific charge of electron by magnetic focusing and by magnetron

The purpose of the lab is to measure the important physical constant, the specific charge of electron. In the first task students determine the constant by means of magnetic focusing. To this end a cathode-ray tube placed in a magnetic field directed along the tube axis is used. Due to independence of the cyclotron frequency of the particle velocity the following effect occurs. The electron beam is focused at the points separated by the distances which electrons traverse for a multiple integer of the cyclotron period. Students observe the focusing by varying the magnitude of the magnetic field, the latter is measured by a coil connected to a milliwebermeter. In the second task students determine the specific charge of electron using a magnetron. Magnetron is a vacuum tube with a cylindric anode and a filament along the cylinder axis as a cathode. Electrons move in the space between the cathode and the anode. A magnetic field in the cylinder is parallel to its axis. The theoretical analysis of electron motion inside the magnetron shows that there is a critical value of the magnetic field at which the electron trajectories are tangent to the inner surface of the anode. If the magnetic field exceeds the critical value the current doesn't flow. Students plot graphs of the current versus the magnetic field and determine the critical value which allows them to determine the desired quantity. Finally students compare the values of the specific charge of electron determined in different tasks.

10. Measurement of current-voltage characteristic of thermionic diode

The purpose of the lab is to determine the specific charge of electron by using the current-voltage characteristics of a thermionic diode which is a vacuum tube with a cylindrical anode and a coaxial filament as a cathode. The current-voltage characteristics is measured when a spatial charge (electron cloud) significantly affects the spatial distribution of electric field inside the tube. By solving an inhomogeneous Poisson equation one can conclude that in this case the current is proportional to the voltage in the power of one and a half (the law of 3/2). The coefficient of proportionality depends on the specific charge of electron. Students measure the current-voltage characteristics for different values of the current through the filament and determine the desired quantity.

11. Millikan's experiment

The purpose of the lab is to determine the electron charge in the famous Millikan's oil drop experiment. In the experiment the charge is measured by using oil drops. The charge of a drop must be a multiple integer of the electron charge. Students observe the motion of the drops in a vertical electric field between the plates of a plane capacitor. Gravity, electric field, and air resistance exert the net force on a drop. Students measure the steady velocities of the drops. To produce charged drops a sprayer is used, the drops acquire electric charge due to friction between a drop and the air. Students observe the motion of drops in a microscope furnished with a scale with hairlines to detect the position of the drops. Students determine the steady velocity by measuring with a stopwatch the time it takes the drop to traverse a distance between the hairlines. The measurement is carried out twice: for the free fall of the drops and for their ascent in the electric field. By performing a sufficient number of measurements students determine the quantum of charge which is the charge of electron.

12. Hall Effect in Semiconductors

When a current passes through a sample placed in a magnetic field, the latter induces nonzero transverse components of the conductance tensor resulting in a transversal potential difference called Hall emf. The hole and electron conductances in semiconductors are usually different. In the lab students verify a linear dependence of the Hall emf on the magnetic field at different values of the current and determine the carrier concentration and conductance of different samples.

13. Hall Effect in Metals

The type of charge carriers in a metal can be of electron or hole type depending on the filling of the outermost electron shell.

In the lab students check a linear dependence of the Hall emf on magnetic field at different values of the current and determine the type, the concentration of charge carriers, and the conductance of different samples.

14. Influence of Magnetic Field on Semiconductor Conductivity

Trajectories of charged particles bend in magnetic field, which results in a shorter effective free path and a quadric growth of resistivity with respect to the field. Two sample geometries are usually used to study the effect: the Hall bridge and the Corbino disk. In the first case we are able to measure both the longitudinal and the transverse components of the resistivity tensor. For the disk only the longitudinal component can be measured.

The experimental setup consists of an electromagnet, a fluxmeter, and a measuring circuit with a digital voltmeter. Samples of n-type InSb in the form of a disk or a plate are studied.

At first students calibrate the electromagnet using the fluxmeter. Then they measure the voltage drop across the sample as a function of the current through the magnet windings and verify that the magnetoresistance is independent of the field direction. Using the results obtained students determine the concentration of charge carriers and their mobility.

15. Dia- and Paramagnets

All nonmagnetic substances can be divided into two groups: dia- and paramagnetic according to the direction of the magnetic moment induced by the external field. Diamagnetism is inherent to all substances because it is due to the orbital motion of electrons. According to Lenz's law electrons tend to move in such a direction as to oppose an external influence. Paramagnetism is a spin related effect which results in an additional interaction between the magnetic moment and the external magnetic field. A substance shows dia- or paramagnetic properties depending on which effect prevails.

The lab setup includes an electromagnet and a precision scale. Students are to define magnetic susceptibility of a number of samples. To do so they calibrate the electromagnet using a fluxmeter and measure the sample weight as a function of the magnetic field.

16. The Curie-Weiss Law

Substances with nonzero atomic magnetic moment are paramagnets. In the external magnetic field the moments align with the field. Temperature is a disordering factor, so magnetic susceptibility decreases according to the Curie–Weiss law because of thermal motion. In ferromagnets thermal motion does not prohibit residual magnetization at finite temperatures, instead a phase transition at Curie point occurs. At temperatures higher than the transition temperature a ferromagnet demonstrates paramagnetic properties and its susceptibility is described by the Curie–Weiss law.

The experimental setup consists of an oscillatory circuit whose inductance coil resides in a thermostat. The sample under study is placed inside the coil and the sample magnetic susceptibility influences the inductance. Students measure the oscillation frequency of the circuit as a function of temperature and verify the Curie–Weiss law. Using the curve obtained they determine Curie point for a gadolinium sample which is close to room temperature.

17. Curie Point

At some temperature referred to as the Curie temperature the ferromagnet spontaneous magnetization vanishes. This is accompanied by changing a number of physical properties of the ferromagnet such as heat capacity, heat and electric conductivity, and magnetic susceptibility. A second order phase transition takes place, i.e. thermodynamic potentials change continuously but their derivatives are singular. In the lab students determine Curie point by observing temperature dependence of resistivity and magnetic permeability.

The setup consists of a nickel helix placed into a furnace. The resistance is measured by a digital voltmeter. The temperature is determined by means of a calibrated thermocouple.

Students obtain the temperature dependence of the resistance by heating and cooling the sample and then determine the Curie temperature.

Measurement of the magnetic susceptibility requires a more sophisticated technique. In this case two coaxial inductance coils are employed with a sample placed inside them. For steady parameters of the AC through the magnetizing coil the current in the measuring coil depends on the magnetic permeability of the sample. Thus one obtains temperature dependence of the magnetic permeability by heating the sample. In this part of the lab students measure the current in the measuring coil as a function of the thermocouple emf and determine the Curie temperature.

18. Hysteresis Loop (static method)

Due to residual magnetization a relation between magnetic induction (B) and magnetic field (H) in ferromagnets turns out to be ambiguous and path dependent. A curve in the coordinates (H,B) which an initially demagnetized sample follows is called the main magnetization curve. For a cyclic magnetization the dependence $B(H)$ is a closed curve restricted by a saturation hysteresis loop.

To observe magnetization curves and the hysteresis loop a toroidal core with two windings, magnetizing and measuring, is used. In the static method a ballistic galvanometer operating in a pulse mode is connected to the measuring winding. A deflection of the galvanometer mirror is proportional to a change of the sample magnetic induction.

Students assemble a measuring circuit and observe the hysteresis loop and the major magnetization curve for the sample which has been previously demagnetized in an alternating magnetic field.

19. Hysteresis Loop (dynamic method)

The usage of ferromagnetic materials in AC devices, e.g. in coil cores motivates studying a magnetic substance in an alternating magnetic field. The main parameters, such as coercive force, magnetic permeability, a heat released during magnetization, and others which depend on the field frequency are of practical value. In the lab we study the ferromagnet parameters at the frequency of 50 Hz.

A toroidal core with two windings, magnetizing and measuring, is used. The measuring winding is connected to a capacitance integrator and the capacitor voltage is displayed on the oscilloscope screen. Students determine electric parameters of the measuring circuit, calibrate the oscilloscope channels, and obtain a graph of the initial magnetization curve and the saturation hysteresis loop. Finally they determine the core parameters.

20. Parametric Resonance

Due to inevitable external influences and thermal fluctuations there are always some small oscillations with the resonant frequency in a circuit. By periodically varying the circuit parameters one can significantly increase the amplitude of these oscillations.

To realize an electrically-tunable inductance a coil with a core which has two additional biasing windings is used. In one of them a DC maintains the working point on the hysteresis loop. At this point the rate of differential magnetic susceptibility is maximal. The other winding is supplied with AC.

To eliminate ordinary inductance excitation two toroidal coils with the oppositely connected windings are used.

The experimental setup includes an oscilloscope, a generator, measuring instruments, and a parametron: a factory made circuit with coils and a capacitor. Students assemble the circuit; make sure that oscillations are really parametric by increasing the circuit resistance; obtain the hysteresis loop and measure the parametron output voltage as a function of frequency. The results allow them to determine the amplitude of the circuit inductance oscillation and the resonant frequency.

21. Study of Gas Discharge Plasma in Ne

Study of gas discharge has resulted in important discoveries and emergence of new fields of physics.

The current-voltage characteristic of a gas discharge has a lot of features; different parts have special names and the corresponding discharge regimes are used in different applications. In the case of a low current and without a bulk charge the electric field is uniform along the whole distance between the electrodes. This type of discharge is called the Townsend discharge. In the case of a strong current the electric field becomes essentially nonuniform and the plasma parameters such as light intensity, electric potential, and electronic and ionic density depend on the longitudinal coordinate. This is a glow discharge. Visually it looks like a number of alternating light and dark sections of different length.

The probe method is an important tool of plasma investigation. A voltage is applied to the electrodes placed in plasma and the current-voltage characteristic is measured.

The experimental setup includes a gas discharge tube with soldered probes, a power supply unit, and measurement instruments.

Students measure current-voltage and probe characteristics. Using the results they determine the main plasma parameters: electron concentration and temperature, ionisation degree, plasma frequency, and Debye length.

22. Inductive Gas Discharge

A high frequency electric field is one of the ways of creating plasma. The main part of the experimental setup is a gas discharge tube placed in a solenoid. A high frequency current passing through the solenoid induces a vortex of electric field, which results in a discharge (this type of discharge is called circular or inductive).

Besides a gas discharge tube with soldered probes the experimental installation includes measuring devices to determine the probe characteristics and a vacuum system to vary the pressure in the tube.

Students measure the current-voltage characteristics on the probes at different pressures and estimate the main plasma parameters.

23. Relaxation Oscillations

Ohm's law is not applicable to the gas discharge tube. The current starts flowing only when the ignition voltage is exceeded and its magnitude leaps right away to a certain value. It is essential that the glowing discharge vanishes at a voltage somewhat lower than the ignition voltage and within some range of voltages the current changes almost linearly. These features allow the glowing discharge to be used as a voltage stabilizer and as a threshold device to discharge the capacitor in the relaxation oscillator.

Students have at their disposal a gas discharge tube, a power supply unit, an oscilloscope, a generator, and some measurement tools. As a part of the lab assignment they assemble the studied circuits.

Students measure a current-voltage characteristic of a stabilitron and get acquainted with the operation of a relaxation oscillator whose parameters they determine.

24. Spectral Analysis of Electric Signals

This work is aimed at studying spectral composition of electric signals. The simplest situations which can be come across in engineering such as a sequence of rectangular pulses, amplitude-modulated harmonic oscillations are considered.

The experimental installation includes a heterodyne spectrum analyser, generators of rectangular and special-shape pulses, and an oscilloscope.

Students get acquainted with the sequential heterodyne method of spectral analysis, observe a variety of signals and compare the experimental results with the theory.

25. Synthesis of Harmonic Signals

An arbitrarily complex signal can be decomposed into a number of simple ones and vise versa. By summing certain harmonic oscillations any signal can be reproduced with a preset accuracy.

The experimental setup includes an oscilloscope, an electronic summation unit, and a generator of harmonic oscillations which is able to produce six multiple harmonic components simultaneously.

Students are to calculate the basic signal frequency, the amplitudes of multiple harmonic components and then to generate a signal of a given shape (a sequence of triangular pulses).

IV. Optics

1. The Michelson interferometer

In the lab the Michelson interferometer is studied, in which two-beam interference takes place. The path-length difference in the interferometer reaches several centimeters therefore to observe an interference pattern a highly coherent light source is required. In the experimental setup helium-neon laser is used. Measuring some features of the interference pattern makes it possible to determine the light wavelength. Due to motion of the interferometer mirror the pattern displays intensity variations which are not related directly to the path-length difference. The variations arise because of the Doppler effect, the change in the frequency of light upon reflection from the moving mirror. To study the effect the installation includes a frequency counter connected to a photomultiplier.

2. Rotation of polarization of light

The purpose of the lab is to study phenomenon of rotation of polarization of light propagating through an optically active medium and through a medium placed in a magnetic field. Optical activity of a medium is a special case of birefringence. In an optically active medium the polarization rotates as light travels through the media. This phenomenon takes place due to a difference in the speed of propagation for the waves circularly polarized in the opposite directions. The optically active substances used in the lab are water solutions of glucose and fructose. The rotation angle is measured by means of a polarimeter for different concentrations of the solutions. The polarimeter allows an observer to compare the visual intensities of the two components of light with different polarizations passed through the polarimeter by adjusting the rotation angle of the analyzer. Also an optically active medium can be placed in a strong magnetic field in order to determine the Verdet constant, the ratio of the rotation angle per unit length to the field magnitude.

3. Study of hologram

In the lab a hologram is studied. Hologram, unlike photo, is intended for recording and reproducing of three-dimensional images. An image is reproduced by restoring the three-dimensional wave field of a recorded object. In the lab students determine parameters of a hologram of the simplest object, a point light source, and study a hologram of a three-dimensional object. The hologram of a point is just a recorded interference pattern between plane and spherical waves. For the hologram of a point source the students are to determine a distance between the source and the hologram and to explore focusing properties of the hologram. For the hologram of a three-dimensional object they observe the real and the virtual image, estimate the angle of incidence of reference wave and the object size. Finally students verify that the whole image can be reproduced by a small part of a hologram.

4. The Talbot effect

In the lab one peculiar aspect of diffraction is studied, namely, repetition of image of a periodic structure aka the Talbot effect which is in conflict with the laws of geometrical optics. In the lab several gratings are used as periodic structures to observe the Talbot images. At first students determine spacings of the gratings in two ways: measuring the parameters of optical image and measuring the parameters of a diffraction pattern. After that it is possible to verify the Talbot effect experimentally and to determine the spacings by locating the positions of self images. In the final part special gratings (mires) are studied.

5. Interference of laser radiation

In the lab an interference pattern of laser radiation is studied. A helium-neon laser is used as a source. Students observe an interference pattern produced by two coherent beams obtained by splitting the outgoing laser beam. The classical scheme of the Michelson interferometer is used. To produce the pattern a Fresnel parallelepiped and polarizers are utilized. Light intensity is detected by a photodiode connected to an oscilloscope. A signal displayed on the oscilloscope screen is due to a periodic variation of a path-length difference between the two beams. The latter is controlled by a piezoelectric crystal on which a mirror inserted in one of the interferometer legs is mounted. Analysis of the displayed signal allows students to verify theoretical assumptions about the laser spectrum which in our case consists of sequential longitudinal modes in the Maxwell gain contour.

6. Helium-neon laser

In the lab an optical-quantum generator (laser) is studied. Laser is a light source with a long coherence length. In the lab a continuous wave laser is studied in which a gain medium consists of a mixture of helium and neon gases. Optical amplification is achieved due to stimulated electronic transitions between the excited levels of neon. Helium is used for transfer of energy to neon atoms by collisions. Atoms of helium are ionized via electron impact. The first task is to determine the gain constant of the HeNe laser using an additional laser, a grid, mirrors, photodiodes, and a computer. After that students are to assemble a model of laser using a tube and two mirrors located coaxially on the both sides. Adjustment of the optical system is carried out with an aid of an additional laser. Upon assembling the laser its polarization and transverse modes of emission are studied.

7. Fourier transformation in optics

The purpose of the lab is to study spatial Fourier transformation which applies to determine the wave field of light passed through different structures: gratings, slits, transparencies, etc. The Fourier transformation of the wave field can be directly observed at the back focal plane of a lens. In the lab students determine the parameters of the gratings and the slit width in two ways: by analyzing the optical image and by analyzing the diffraction pattern which is the spatial spectrum. Modifying the spectrum one can replicate the optical image. To this end the spatial spectrum is dissected by a grating. In the final part of the lab students study how a slit diaphragm placed at the back focal plane of the lens affects the image produced by the lens.

8. Birefringence

In the lab students study propagation of light in an anisotropic medium. In an isotropic medium the propagation of light does not depend on polarization: all polarizations are equivalent. In an anisotropic medium the propagation direction depends on polarization, this phenomenon is known as birefringence. A crystal serves as an example of anisotropic medium. Crystal lattice possesses a symmetry which determines the symmetry of physical properties. In particular the electrical permittivity of a uniaxial crystal depends on the direction of the electric field vector and for any two orthogonal directions the permittivity is the same. This fact results in a possibility to determine the optical axis, to distinguish ordinary and extraordinary waves, and to find the respective refractive indices. In the lab students study propagation of ordinary and extraordinary waves in a triangular prism made of Iceland spar which is a uniaxial crystal. The experimental results allow them to verify the theoretical predictions relating refractive index to the direction of propagation of the ordinary and extraordinary waves.

9. The Pockels effect

The purpose of the lab is to study propagation of light in an anisotropic medium. Students study the optical properties of the medium and how these properties are affected by an electric field, the phenomenon known as the Pockels effect. A uniaxial crystal of lithium niobate is used as a sample. The optical properties of the sample are studied via observation of an interference pattern which resembles the Maltese cross. The pattern arises due to an interference between the projections of ordinary and extraordinary waves on the allowed direction of a polarizer. The pattern dependence on the rotation angle of the polarizer is studied. The Pockels effect consists in producing birefringence in a crystal subjected to an electric field. For a uniaxial crystal which does not possess the center of symmetry the effect induces a linear dependence of the refractive index on the electric field for special orthogonal polarizations. To visualize the effect students use it to transform a linearly polarized light into the circular one. For quantitative estimating of the effect the experimental setup includes a photomultiplier connected to an oscilloscope. Observing Lissajous figures it is possible to monitor a relation between a phase shift between polarized components and the electric field amplitude.

10. Study of prism by means of goniometer

The purpose of the lab is to study spectral characteristics of a triangular prism by means of a goniometer, the instrument that is specially designed for precision angle measurement. Students are to measure minimal deviation angles of spectral components of mercury lamp and using the known spectrum of the lamp they determine the refractive index of the prism material. Students also determine spectral characteristics of the prism: its angular dispersion and resolving power. Finally the measured characteristics of the prism are compared with similar characteristics of some gratings.

11. Tunneling of microwaves

The purpose of the lab is to study penetration of radiation into a medium in the case when the angle of incidence exceeds the critical angle. This phenomenon is named tunneling. To explore the phenomenon students assembe the Michelson interferometer and study microwave interference. The phenomenon is observed in a parallel-sided adjustable air gap between two fluoropolymer prisms. A microwave generator serves as a wave source, a trumpet antenna is used to detect signal. Then students measure intensities of the passed and reflected waves as a function of the gap width and verify the theoretical assumptions. Finally the Michelson interferometer is assembled, the air gap is employed as a semitransparent mirror. Using the interferometer students determine the wavelength and also the refractive index of the fluoropolymer plate.

12. Newton's rings

In the lab dual-beam interference is studied. Two-beam interference takes place in thin films and it is often used to measure their thickness. In the lab two-beam interference is observed in reflected light in the air gap between a plane surface and the convex surface of a lens pressed against it. The interference pattern allows one to draw some conclusions about the shape of the lens and the phase shift of light reflected from optically dense medium. The pattern is observed in a microscope. Both natural and monochromatic light is used. Also students observe a beat which arise when two patterns due to different spectral components are superimposed.

13. The Jamin interferometer

In the lab an interference pattern is used to measure the refractive index of gas. The measurement is performed by means of a sensitive device — the Jamin interferometer. The pattern observed in the interferometer is the result of interference between two beams passing through and reflected from two thick one-side silver-coated plates. On the way of one beam a plate with a turning screw is placed. The plate contributes a path-length difference which is determined by the displacement of interference pattern observed in monochromatic light. When the path-length difference has been measured a transparent container with a gas sample is placed on the way of one beam. The refractive index is then determined by observing the displacement of the interference pattern. High sensitivity of the Jamin interferometer is due to considerable shift of interference pattern under slight variation of the refractive index. The results of the measurement of refractive index allow students to determine the concentration of gas molecules.

14. The Rayleigh interferometer

In the lab the refractive index of a gas is determined by observing interference pattern in the Rayleigh interferometer. In the interferometer interference takes place in the classical double-slit Jung's scheme. On the way of light beam passing through one slit a compensator is placed which contributes adjustable path-length difference. By observing the shift of interference pattern it is possible to relate the actual path-length difference of the two beams to the position of control knob of the compensator. Upon calibrating the interferometer a transparent container with a sample of gas is placed on the way of one beam and the refractive index is then determined by the observed displacement of interference pattern. To avoid undesirable complications the optical setup of the installation meets the condition of Fraunhofer diffraction. This is achieved by using a lens that moves the interference pattern from infinity to the focal plane of the lens. In this case the theoretical dependence of intensity on coordinate is rather simple and permits a straightforward experimental verification. For observer convenience the pattern is stretched by means of a cylinder shaped lens.

15. Fabry–Perot interferometer

The purpose of the lab is to study the Fabry–Perot interferometer, a spectral analyzer of a high resolving power. In the interferometer a multiple-beam interference takes place due to multiple reflections from parallel mirrors. The interference pattern consists of concentric rings at the focal plane of a lens and it is observed with the aid of a telescope. A reading microscope is employed to measure the rings diameters. By measuring the diameters of the rings observed for mercury and sodium lamps students determine the distance between the mirrors and the spectral characteristics of the interferometer: its resolving power, dispersing area, finesse and linear dispersion. Using the interferometer it is possible to estimate the hyperfine splitting of a mercury spectral line.

16. Scanning interferometer

The purpose of the lab is to study the spectrum of a continuous wave laser. A helium-neon laser is used. The spectrum is studied by means of a scanning interferometer that is a high-Q Fabry–Perot interferometer which base varies periodically. The variation is controlled by periodic voltage applied to a piezoelectric crystal. To avoid return of the beam into the laser a polarization isolation is used. The spectrum is detected by means of a photodiode connected to an oscilloscope. The other oscilloscope input is the voltage controlling the base variation. Analyzing the signal on the oscilloscope screen students determine the intermodal distance, a width of neon spectral line and estimate kinetic temperature of the gain medium. Besides it is possible to estimate the characteristics of the Fabry–Perot interferometer: the reflectance, the finesse and the dispersive area.

17. Interference of electromagnetic microwaves

In the lab interference of millimeter range electromagnetic waves aka microwaves is studied. Interference is observed in a parallel-sided plate and in the Michelson interferometer. A klystron serves as a microwave generator and a microwave detector measures the radiation intensity. At first students verify the Malus law. For microwaves a metal plane can be utilized as a mirror, a metal grating with a spacing about one millimeter is used as a semitransparent mirror. These objects are used to simulate the parallel-sided plate and the Michelson interferometer. The latter is employed to determine the radiation wavelength and the refractive index of a parallel-sided teflon plate.

18. Study of light diffraction

The important property of wave processes is diffraction. The purpose of the lab is to study diffraction of light. The latter can be easily observed by means of a microscope and a telescope implemented in the lab. Both Fresnel and Fraunhofer diffraction is studied using a slit with adjustable width. The wave field is calculated graphically by means of the Huygens-Fresnel principle. The obtained results are then experimentally verified. In the lab Fraunhofer diffraction on two slits is also studied. Fraunhofer diffraction is directly related to resolution of optical instruments. Another task is to study how diffraction affects resolution of the microscope. Students study how the image observed in the microscope is affected by varying the width of a light beam, which allows them to verifiy experimentally the Rayleigh criterion. The phenomena observed in this lab clarify the role of diffraction in image formation in optical instruments.

19. Study of diffraction grating with the aid of goniometer

In the lab the parameters of diffraction gratings are determined by means of a goniometer. The set of gratings includes an amplitude grating with a step-wise transmission function and a phase grating. The amplitude grating is made by grooving a metal coated glass plate. The phase grating aka echelle grating is a set of parallel triangular grooves on the surface of glass coated with a reflecting layer. In the lab students explore the spectrum of mercury lamp using the gratings as spectral analyzers. Also they learn how to handle a goniometer, the instrument for precision measurement of angles. In the lab the goniometer is used to measure the deflection angles of diffracted beams. Students experimentally verify the theoretical calculations of the wave field which follows as a result of diffraction on the gratings. Also they determine spectral characteristics of the gratings, namely, angular dispersion and dispersing area, and examine how the width of diffracted beam affects the resolving power.

20. Optical diffraction on ultrasound wave in liquid

In the lab propagation of light through optically non-uniform medium is explored. Optically nonuniform medium is formed by an ultrasound wave in liquid and since the frequency shift of the passing light is negligible the ultrasound wave can be treated as a stationary sinusoidal phase grating. Due to a small phase shift induced by the grating the passed light can be represented as a superposition of three plane waves, this fact is experimentally verified. Cavity with a liquid is illuminated by a parallel monochromatic light beam. Students determine the ultrasound wavelength in two ways: by positions of the diffraction maxima corresponding to different plane waves and via a direct observation of the phase grating made visible by spatial filtering (dark-field method).

21. Study of microscope resolution by Abbe method

In the lab light diffraction and its role in microscope image formation is studied. Light diffraction is a direct consequence of the wave nature of light, which affects significantly image formation in optical instruments. The main objective of the lab is to study how diffraction affects the resolution of a model microscope made of several lenses, a slit with adjustable width, and a set of gratings. Students determine the gratings parameters in two different ways: by analyzing their optical images and diffraction patterns. The next task consists in studying the effects of diffraction on the microscope resolution. To this end students determine the gratings parameters by observing a disappearance of the periodical image on the screen. Another task consists in verifying Abbe theory of image formation. This is carried out by means of spatial filtering which is implemented by modifying a spatial spectrum in the Fourier-plane of the lens. Finally students observe the replication of a slit image by dissecting its spatial spectrum with a grating placed in the Fourier plane of the lens.

22. Study of polarized light

The purpose of the lab is to study polarization of light - the important property of transverse electromagnetic waves. Different ways of producing and analyzing polarized light are implemented in the lab. Those include: transmission of natural light through a polarizer and/or a birefringent crystal and reflection of light from a plane surface. The allowed direction of a dichroic plate is determined by analyzing the light reflected from a plane surface at the Brewster's angle. The principal axes and the lagging for several birefringent crystals are determined by means of a couple of crossed polarizers. A quarter-wavelength plate is used for transformation of a linearly polarized light into elliptically polarized one. The final experiment consists in observing different color and intensity patterns resulted from mixing the polarized beams which allows students to verify theoretical assumptions regarding their interference.

V. Quantum Physics

1. The Compton Effect

The energy of γ-quanta scattered by electrons of graphite is measured by a scintillation spectrometer as a function of the scattering angle. The experimental results allow one to determine electron rest energy.

The source of γ-radiation is ^{137}Cs emitting quanta with the energy of 662 keV. The source is enclosed in a thick-wall lead container with a collimator that forms a narrow beam of the γ-rays coming out of the source. A graphite cylinder 40 mm in diameter and 100 mm high serves as a target. The scattered quanta are detected by a scintillator (crystal of NaI(Tl)) whose output window is in optical contact with a photomultiplier (PMT). The scintillator and the PMT are encased in a light-proof container which is mounted on a horizontal lever that can be rotated around the cylinder. The angle of rotation is measured by a limb. The PMT output signal is amplified and registered by an analyzer that assigns a channel number from 0 to 1023 to the signal. The number is proportional to the energy of γ-quanta absorbed by the scintillator with an accuracy about 1%. The number of counts per second in every of 1024 channels is displayed on a PC screen, the image on the screen is updated every 5 seconds.

This experiment illustrates the corpuscular-wave nature of electromagnetic radiation. An observed broadening of the Compton peak, which is partially due to a systematic experimental error, is of the same order of magnitude as the broadening due to scattering on the electrons of internal orbitals of carbon.

2. Determination of energy of α-particles by measuring their penetration depth in air

A penetration depth of α-particles in air is measured using three different methods and their energy is then determined. Isotope ^{239}Pu emitting α-particles with the energy of 5 MeV is used as a source.

a. Measurement of the penetration depth using Geiger–Mueller counter

A radioactive source is mounted on the bottom of a steel cylindrical container in which a Geiger–Mueller counter can be moved along the cylinder axis. A signal from the counter is amplified and registered by an analyzer. The count rate versus the distance between the counter and the source is measured.

b. Measurement of the penetration depth using scintillation detector

A radioactive source is mounted on the bottom of a steel cylindrical container. The container lid is a glass plate covered with a luminophore on the side facing the source. A photomultiplier cathode is pressed against the glass on the other side. The pressure inside the container can be varied by means of a vacuum pump. A signal from the photomultiplier is amplified and registered by an analyzer. The count rate is measured as a function of pressure.

c. Measurement of the penetration depth using ionization chamber

An ionization chamber is a spherical glass container with two electrodes. The chamber wall serves as one electrode and the other one is located at the chamber center. A bias voltage of 300 Volts is applied to the electrodes. A radioactive source is mounted on the top of the central electrode. The emitted α-particles ionize the air in the chamber letting electric current flow between the electrodes. The pressure inside the chamber can be varied by means of a vacuum pump. A current through the chamber is measured at different pressures.

The lab serves to illustrate the main channel of energy losses by low energy α-particles passing through matter, namely, electronic losses. These three methods give consistent results for the penetration depth, a theoretical value for the particle energy derived from it is close to 5 MeV.

3. Measurement of energy spectrum of β-particles by means of a magnetic spectrometer

A magnetic spectrometer with a "short lens" is used to measure the energy spectrum of β-particles emitted by radioactive nuclei 137Cs and to determine their end-point energy. The spectrometer is calibrated by a peak in the spectrum corresponding to internal conversion electrons.

A radioactive source ^{137}Cs is placed inside a metal tube at one end. The pressure inside the tube is maintained by a vacuum pump around 0.1 torr. A coaxial magnetic coil serves as a lens focusing the decay electrons on a scintillator detector (thin crystal of polystyrene) at the other end of the tube. The lens and several diaphragms ensure that electrons coming to the scintillator have their momentum directly proportional to the current through the coil. Resulting scintillations are detected by a photomultiplier; the output signal is then amplified and registered by PC. A plot of the number of counts per second versus the current is displayed on the screen. The current can be varied between 0 and 5 amps. A sharp peak due to internal conversion electrons, whose momentum is known to be 1013.5 keV/c, is used to calibrate the spectrometer. The end-point energy of β-particles is determined from the Fermi–Kurie plot.

This lab is a version of the classic experiment that points to the existence of neutrinos, albeit indirectly. The experiment serves to illustrate the statistical nature of nuclear decay and to familiarize students with the conventional method of data treatment in nuclear physics, i.e. making cuts to account for the background and fitting theoretical function (the Fermi–Kurie plot) to data.

4. Measurement of total activity of a sample of ^{60}Co by $\gamma - \gamma$ coincidence method

The total activity of a sample of radioactive 60Co is measured by using a cascade emission of two γ-quanta in the decay of nucleus ^{60}Co.

Gamma-quanta coming out of a radioactive source in the opposite directions are detected by two scintillation counters. A counter consists of a crystal of NaI(Tl) and a photomultiplier. The scintillations created by a γ-quantum in a crystal are transformed into an electric pulse by a photomutiplier; the pulse is processed by an analyzer and transferred to a coincidence circuit.

The lab demonstrates the statistical nature of nuclear decay and introduces a student into the basics of the scintillation counter design.

5. Measurement of narrow-beam attenuation coefficients of γ-rays and determination of their energy

Linear attenuation coefficients for a narrow beam of γ-rays in lead, iron, and aluminum are measured. The values obtained are used to determine the energy of γ-quanta.

A sample of ^{137}Cs enclosed in a thick-wall lead container is used as a source. A collimator creates a narrow almost parallel beam of γ-rays that passes through an absorber; the γ-quanta passed are detected by a scintillation counter. A signal from the counter is amplified and registered by an analyzer. The count rate versus the thickness and material of the absorber is measured.

The lab is used to show that the Compton scattering is the main channel of scattering of γ-quanta passing through matter with the energy in the range produced by the source. The mass attenuation coefficients for three different absorbers turn out to be numerically close.

6. Measurement of energy of γ-quanta by means of scintillation spectrometer

The energy of γ-quanta of an unknown source is measured after the spectrometer has been calibrated by a known spectrum of γ-radiation of ^{60}Co.

A crystal NaI(Tl) is used as a scintillator, its output window is in optical contact with a photomultiplier cathode. A signal from the photomultiplier anode is amplified and transferred to an analyzer. If the signal magnitude is in a given narrow window, the analyzer forms pulses counted by a register-type circuit. Then scanning the voltage range from 0 to 10 Volts yields a differential spectrum of energy released in the scintillator.

The lab introduces the basic operation principles of scintillator spectrometer. Besides, the analysis of the energy spectra obtained allows one to draw some conclusions about the processes taking place in the scintillator.

7. The Mössbauer Effect

Resonant absorption of γ-quanta emitted by nuclei ^{113}Sn at room temperature is studied by using Doppler shift of Mossbauer emission and absorption lines. The position of resonant absorption maximum, its numerical value, and the width of the absorption curve are measured. The data are used to estimate the lifetime of an unstable state of ^{113}Sn nucleus and a chemical shift of the nucleus energy in pure Sn compared to its energy in compounds $BaSnO_3$ and SnO_2.

The radioactive source ($BaSNO_3$) is moving relative to the absorber at a constant speed by means of a simple mechanical device. The speed of the source can be varied between 1 and 5 mm/s. Gamma ray photons which have passed through the absorber (tin foil or tin oxide), are then absorbed by a scintillator (NaI(Tl) crystal). Low energy photons coming out of the scintillator are counted by a photomultiplier. The output signal is amplified, registered by an analyzer and finally processed by PC. An absorption intensity versus the speed of the source is plotted on a display screen.

This experiment allows one to observe a macroscopic quantum effect at room temperature using relatively simple equipment (A radioactive source needs replacement once a year). Besides a high degree of precision of the measurements based on the Mossbauer effect is demonstrated. In our case this is a measurement of the relative shift ($\sim 10^{-8}$ eV) of nucleus energy levels in different chemical compounds due to interaction between the nucleus and atomic electrons.

8. Estimation of muon lifetime by measuring azimuthal distribution of cosmic rays intensity

A scintillator "telescope" is used to measure an azimuthal distribution of the hard component of cosmic rays, which allows one to estimate the mean lifetime of muon.

Two scintillators are mounted on a rigid frame which can be directed to an arbitrary point on the celestial sphere. A scintillator consists of a polystyrene slab $400 \times 100 \times 25$ mm in size, the scintillations are detected by a photomultiplier. The signals from the photomultipliers are amplified and registered by a coincidence circuit. The count rate gives an intensity of the hard component of cosmic rays arriving at some azimuth angle. The angular distribution obtained is then used to give a fair estimate of the mean lifetime of muon provided the average energy of muons produced in the upper atmosphere and the atmosphere thickness are known. To improve the results one can suppress the soft component of cosmic radiation by covering the scintillators with a 4 cm layer of lead.

The lab gives an indirect evidence that the hard component of cosmic rays penetrating the atmosphere is mostly due to muons.

9. Experimental Study of Absorption of Secondary Cosmic Rays in Iron and Lead

The intensity of cosmic rays at sea level is measured as a function of the thickness of absorbers made of iron and/or lead by means of a "telescope" consisting of two scintillation detectors connected to a coincidence circuit. The results of the measurement allow one to determine mean free path of soft and hard components of the cosmic rays, their total vertical intensity, and the cross-section of electron-positron pair production in iron and lead.

The setup comprises two scintillation counters made of polystyrene slabs $40 \times 10 \times 2.5$ cm in size doped with scintillation impurities. The scintillators are mounted on a vertical frame and separated by a distance of 40 cm. Scintillations are detected by photomultipliers whose signals are amplified and then analyzed by a coincidence circuit. The number of coincidence counts is shown on a digital display.

The lab provides an experimental evidence that the cosmic rays at sea level include muons and electrons, the latter being the decay product of the former. The electrons lose their energy mostly due to bremsstrahlung and electron-positron pair production. The muon energy losses are due to ionization.

10. Experimental Study of Thermal Radiation and Measurement of Stephan–Boltzmann and Planck constants

The temperature of a black body simulator (BBS) is measured by means of a pyrometer and a thermocouple, which allows one to determine Planck and Stephan–Boltzmann constants. Thermal radiation of several objects of various emissivities is observed.

The experimental setup consists of a disappearing filament pyrometer, BBS, three specimens, a current source, and digital voltmeters. The BBS is realized as a ceramic tube of 3 mm in diameter and 50 mm in length sealed at one end. The tube is placed inside a case that serves as a thermal insulation. A nichrome winding around the tube serves as a source of heat. The radiation coming out from the tube cavity and especially from its bottom is practically very close to black body radiation. Three specimens whose radiation is studied are:

- ◇ a ceramic tube heated from inside by a nichrome wire with several rings of different materials;
- ◇ a tungsten filament of electric bulb;
- ◇ a neon lump.

The lab illustrates Planck theory of radiation.

11. The Curie–Weiss Law and Exchange Interaction in Ferromagnet

A temperature dependence of magnetic susceptibility of a ferromagnet (metallic gadolinium) is measured in the paramagnetic domain, above the Curie point. The measured dependence allows one to determine the Curie temperature of the ferromagnet and to estimate the energy of exchange interaction.

A ferromagnetic specimen is placed inside a coil that serves as inductance of LC circuit, the latter being a part of a high frequency generator. A resonant frequency of the circuit is shown on a digital display. The specimen is a Teflon capsule filled with small Gd granules less than 0.1 mm in size to suppress eddy currents which otherwise would obscure the experimental results. The capsule can be moved in and out of the inductance coil. A resonant frequency of the LC circuit with and without the capsule is measured when heating the coil in a small electric oven from 10 °C to 70 °C. The specimen temperature is measured by a copper-constantan thermocouple, connected to a digital voltmeter. One end of the thermocouple is in thermal contact with the specimen, the other one is in a Dewar flask at room temperature.

This lab illustrates one of the fundamental laws of ferromagnetism. Besides, using the Heisenberg theory one can derive a numerical estimate of the exchange integral in metallic Gd from the Curie temperature. Thus an intrinsic quantum characteristic of ferromagnet is found by means of the macroscopic classical measurement.

12. Electron Paramagnetic Resonance

Electron paramagnetic resonance (EPR) is experimentally studied, electron g-factor and the EPR width are measured, and fine and hyperfine structure of the EPR line is observed.

The experimental setup is basically a radio spectroscope operating in the 100–200 MHz range. The principal part of the spectroscope is an LC-circuit made of several windings of inductor coil and a two-plate capacitor. An ampoule containing thin powder of radical Diphenylpicrylhydrazyl (DPPH) can be inserted inside the coil. The inductor is placed between two coaxial magnetic coils which provide a steady magnetic field in the sample of DPPH. A small modulating field is generated by additional coils. The electromagnetic oscillations in the LC-circuit are induced by a radio-frequency generator. A signal from the circuit is displayed on the oscilloscope screen. A sharp peak due to diminishing Q-factor is seen when paramagnetic losses take place.

The lab serves to illustrate the basic principles of EPR method. The shape of EPR line gives some clues to spin-spin and spin-lattice interaction of free radicals in DPPH.

13. Nuclear Magnetic Resonance

In this lab nuclear magnetic resonance (NMR) is studied, the NMR signal is observed on the nuclei of hydrogen (water and rubber), deuterium (heavy water), and fluorine (Teflon). The g-factors of the nuclei are measured.

The principal part of the experimental setup is a weak signal RF-generator which is basically an amplifier with positive feedback. The latter maintains a continuous generation. A coil with a specimen inside is a part of the generator. A constant magnetic field in the specimen is created by an electromagnet. There is also an additional alternating magnetic field with a small amplitude and the frequency of 50 Hz induced in the specimen by a supplementary coil, so that the field in the specimen takes a resonant value twice during the period. When NMR is achieved the absorption of the energy from the HF-electromagnetic field rises, Q-factor of the LC-curcuit drops, and the generation amplitude decreases. The NMR signal is displayed on the oscilloscope screen.

This experiment provides a good introduction into physics of nucleus (a scale $\sim$1 fm). The measured values of g-factor are in a fair agreement with those predicted by the nuclear shell model.

14. Measurement of energy gap in semiconductor

Conductivity of a pure semiconductor (silicon or germanium) is measured as a function of temperature. The results are used to determine the numerical value of the energy gap of the semiconductor.

A small slab of crystalline semiconductor of $3 \times 5 \times 30$ mm in size and a thin copper wire 20 m in length are heated inside an electric oven. Depending on the experimental setup, the electrical resistance of two specimens is measured either by means of a high-precision digital voltmeter (DC measurement), or using a Wheatstone bridge and a resistance decade box (AC measurement). In both cases the current through the specimens doesn't exceed 1 mA. The temperature inside the oven is determined by means of a copper-constantan thermocouple. One junction of the thermocouple is placed inside the oven, the other one is in a Dewar flask at room temperature.

This lab demonstrates the difference in thermal behavior of conductors and semiconductors. The results serve to illustrate the theory of band structures in which the width of the semiconductor energy gap defines the exponential growth of the conductivity under heating.

15. Study of Semiconductor Photoconductivity

In this lab photoconductivity of semiconductors is studied. A photocurrent spectral dependence is measured, which allows one to determine the semiconductor energy gap and the excitation energy of impurities.

Thin films or thin slices of crystals of CdSe and CdS doped with copper are used in this experiment. The minimal photon energy required to excite the impurities in these semiconductors lies in the visible light domain. A small dark current and a high light yield make it possible to perform the experiment without light modulation. The light from a source is focused on the input slit of a monochromator that cuts out a narrow band from the incident light spectrum. The light passed through the monochromator strikes the semiconductor cell. A bias voltage and a load resistor are used in series with the semiconductor. The voltage across the resistor is proportional to the photocurrent, it is measured by a digital voltmeter.

The lab serves as a good illustration of the theory of band structures in semiconductors. The plot of photocurrent versus wavelength shows directly the energy gap of the semiconductors and the excitation energies of the copper impurities.

16. Measurement of built-in potential of p-n junction

Electrical resistance of a p-n junction is measured as a function of temperature and the built-in potential is then determined.

The experimental setup includes a Wheatstone bridge and a resistance decade box. A radio frequency generator of rectangular pulses is used as a power source. The resistance decade box and a silicon diode are connected to known and unknown legs of the bridge, respectively. An oscilloscope serves as zero indicator. The diode is placed inside an electric heater. The diode temperature is measured by a thermocouple whose hot junction is in thermal contact with the diode and the cold junction is placed inside a Dewar flask at room temperature. The measurements are done in a temperature range between 25 °C and 70 °C.

The lab serves as introduction to physics of p-n junction.

17. Tunneling in semiconductors

A current-voltage characteristic (VI curve) and the main parameters of a tunnel diode are measured.

The measurements employ three electrical networks: a network for measuring the VI curve of the diode, a network for observing the VI curve on the oscilloscope screen, and an oscillator circuit in which the tunnel diode is used as its principal element. The setup also includes an ammeter, a digital voltmeter, an oscilloscope, and a Wheatstone bridge.

This is the second lab which illustrates physics of p-n junction.