PHYS 305
Experiments in Modern Physics Lab. Manual

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Chapter 1

MILLIKAN'S OIL DROP EXPERIMENT

Purpose

The purpose of this experiment is to measure the charge of the electron, and show that it is quantized with smallest value of 1.6 x $10^{-19}C$.

Introduction

Greek philosophers debated whether matter is infinitely divisible or is, instead, composed of discrete atoms (in Greek $\alpha\tau o\mu o\sigma$ meaning "uncuttable") as taught by Democritus in the fifth century B.C. During the nineteenth century A.D. the atomic idea was the basis for various successful theories of chemistry and physics, most notably the theory of chemical combination (Dalton) and the kinetic theory of gases (Maxwell). Iret there remained competent scientists who doubted the reality of atoms as late as 1900. They followed Ernst Mach (1836-1916) in adherence to the philosophical principle of empiricism whereby physical theory must exclude any concept that is not directly observable. In fact, it was not until the present century that the atomicity of matter or of any of its attributes (e.g. charge) was directly observed. After all, one atom of lead weighs only 3.2 x $10^{-22}g$; one electronic charge is 4.8 x $10^{-10}statcoulombs$; the quantum of angular momentum is 6.7 x $10^{-2}cm^2s^{-l}$; and the energy of one quantum of red light is 3.2 x $10^{-12}ergs$. Whereas the units of these measures are physical quantities of palpable magnitude, readily measured with the instruments invented by nineteenth century physicists, the atomic quantities are such minute fractions of their units of measure as to have defied measurement by the best experimentalists of that century.

Then, in 1907, Robert Millikan's young collaborator, Harvey Fletcher, got the idea of watching the motion of a single, charged, microscopic oil droplet under the influence of gravity and a uniform electric field between two parallel metal plates. He produced microscopic droplets with an "atomizer", like a common nasal spray, illuminated the droplets from behind, observed individual droplets as unresolved pinpoims of diffracted light, and timed their motion between fiducial marks in the focal plane of a horizontal microscope as they switched the voltage between the plates on and off. Some droplets carried a few more electrons than protons, or vice versa, and could be suspended or drawn upward against the force of gravity by application of an electric field of the order of a thousand volts per cm. Droplets were tracked up and down many times, sometimes for hours, to reduce random errors in the measurements of the terminal velocities of the motions under the forces of gravity, viscous drag, and electricity in the presence of the fluctuations of Brownian motion.

The oil drop experiment proved the atomicity of electricity (i.e. that the droplets always carried integer multiples of a charge quantum e), determined the value of e with an estimated error of ±0.2%, provided thereby the key to the accurate determination of the mass of the electron and Avagadro's number (from the previously measured values of e/m and $F = Ne$), and won Millikan the Nobel Prize. It turned out that his result was off by a systematic error of -0.6% due to an error in the viscosity of air which was corrected in 1930. The uncertainty of the currently accepted value is ±0.0003% (3 ppm).

For an interesting presentation of the physics and history of the discoveries of the electron and other fundamental particles, see Weinberg (1983).

Theory of the Experiment

Consider a spherical oil droplet of radius a and density ρ falling at a terminal velocity ν through air of density $\rho\prime$ and viscosity coefficient η. If a is large compared to the mean free path of the air molecules, then the gravity and buoyancy forces acting on the droplet are balanced by a drag force $6\pi\eta a\nu$ according to Stoke's law for the streamline motion of a sphere through a viscous medium. Actually, the experiment must employ oil droplets which are light enough to be suspended or drawn upward by the electric force exerted on just a few (1 to ∼10) electronic charges by a field of a thousand volts/cm. Such droplets have radii that are typically not very large compared to the mean free path of air molecules, which is 2.2 x $10^{-6} cm$ at normal temperature and pressure according to the CRC Table. The equation of motion for a spherical oil drop can be written as

$$\mathrm{m}\frac{d\nu}{dt} = \frac{4}{3}\pi a^3(\rho - \rho\prime)g - qE - 6\pi\eta a\nu$$

where g is the acceleration of gravity. If the droplet carries a charge ne and is moving upward with terminal velocity ν under the influence of an electric field V/d between two parallel plates separated by the distance d and a potential difference V, the equation of motion is

$$m\frac{d\nu}{dt} = \frac{4}{3}\pi a^3(\rho - \rho\prime)g - ne\frac{V}{d} - 6\pi\eta a\nu$$

This equation can be easily solved:

1. If there is no applied electric field ($E = 0$) and oil drop moves with terminal velocity;

$$\nu = \frac{\frac{4}{3}\pi a^3(\rho - \rho\prime)g}{6\pi\eta a} = \frac{2}{9}\frac{a^2(\rho - \rho\prime)g}{\eta}$$

The radius of oil drop is

$$a = 3\sqrt{\frac{\eta\nu}{2(\rho - \rho\prime)g}} \tag{1}$$

2. If oil drop has been held stationary (η=0) using electric field;

$$\frac{4}{3}\pi a^3(\rho - \rho\prime)g = qE$$

We find

$$\text{q}=\frac{4}{3}\pi a^3(\rho - \rho\prime)g\frac{d}{V} \tag{2}$$

Using equation (1) and equation (2) and solving for q, we obtain

$$q = \frac{9\sqrt{2}\pi\eta^{3/2}}{(\rho - \rho\prime)^{1/2}g^{1/2}}\frac{d}{V}\nu^{3/2} = c\frac{\nu^{3/2}}{V} \tag{3}$$

where $c = 2x10^{-10}$. Many measurements of $q = ne$ for drops of various radii will yield a collection of values; presumably, each is close to an integer multiple of the fundamental unit of charge. When the numbers of unit charges involved in each of the measurements has been figured out, then each measurement, divided by the proper integer number, yields a value of e. A plot of $c\nu^{3/2}$ against V should show data points clustered around lines with slopes equal to ne (n = 1,2,3,...).

Preparatory Questions

The Millikan apparatus in Modern Physics Lab has two parallel plates separated by approximately 0.6 cm and a high-voltage power supply (0 to 600 Volts). Each time you start a new observation with zero field and a squirt from the atomizer you will see a myriad of droplets falling through the field of view. Your problem will be to pick a droplet that is of a size such that, if it carries a charge of a few electrons (e.g.1-3e), you will be able to pull it upward with the available electric force. To judge which droplet to pick you must estimate the terminal fall velocity and holding voltage of a suitable droplet. The velocity of a droplet is determined from a measurement of the time it takes it to fall a distance which can be seen in the eyepiece reticle. The distance has to be taken about z=0.1 cm.

Problem 1: Calculate the time of fall of a droplet (z=0.1 cm) which, if it carries a charge of 1e, can be held stationary with a voltage of 200 Volts.
Problem 2: Describe another completely independent method for determining the value of the electron charge.

You can obtain results of impressive accuracy in this experiment provided you take care in reducing random errors of measurement. The most important thing of all is to select appropriately sized droplets carrying very few elementary charges - 1e to 3e or 4e. Make a preliminary analysis of the data for each droplet immediately after you obtain it so that you can perfect your judgement as to which droplets to select and what voltages to use. The timing measurements are like a video game in which practice makes perfect. N repetitions of any given measurement will reduce the random error of the mean in proportion to $(N)^{1/2}$. The most important source of systematic error is probably the voltage measurements. To estimate the error you should check the voltmeter against other similar ones and against the electrostatic voltmeter.

References

P. R. Bevington & D. K. Robinson 1992, Data Reduction and Error Analysis for the Physical Sciences, 2nd Edition, McCraw Hill.

R. A. Millikan 1911, "On the Elementary Electrical Charge and the Avagadro Constant." Phys. Rev. 32, 349.

S. Weinberg 1983, "The Discovery of Subatomic Particles." Scientific American Books, New York.

Procedure

A schematic diagram of the apparatus is shown in Figure 1.1.

1. Adjust the eyepiece so the reticle is in sharp focus for your eye.

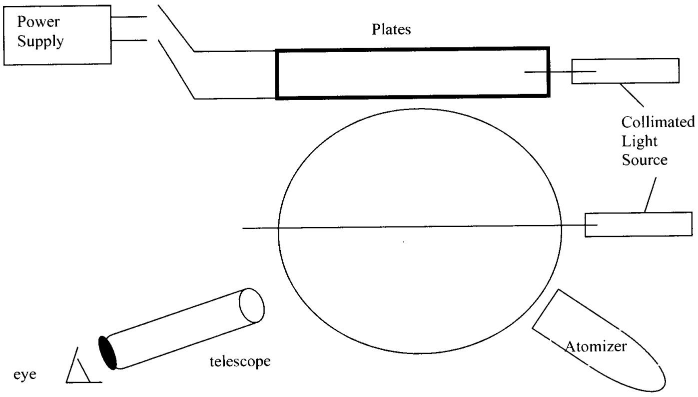

Figure 1.1: Schematic side and top view of the Millikan's Oil Drop apparatus

2. Spray droplets of oil from the atomizer through the port into the top chamber. As the droplets drift down some pass through the tiny hole into the fiducial volume where they are illuminated by a collimated light as illustrated. When you see a droplet through the microscope as an unresolved point of diffracted light drifting slowly downward, attempt to arrest the droplet's fall by applying a voltage across the parallel plates. If the droplet moves downward more slowly under the influence of the electric force, then clearly the droplet is charged and an increase in voltage may arrest or reverse its motion. If the droplet accelerates downward under the action of electric force, the voltage should be reversed. If the electric

field has no effect, then the droplet is not charged at all. Try another droplet. When you catch one that works, i.e. it drifts slowly downward (∼30 s fall time indicates the drop has about the optimum weight) with no voltage and can be pulled up by applying a voltage (∼180 V indicates that there are only a few charge quanta on the drop).

3. Using as your race track the gap between horizontal lines of the reticle in the focal plane of the telescope, measure the free-fall times with the voltage off record the voltage that keeps it stationary on one droplet. Repeat as many times as possible or as long as you have patience. When you think you have your first really good set of repeatable data for one droplet, stop and analyze it, and derive the value of the charge on the droplet. If everything seems reasonable and your value is close to a small (∼1-5) integer multiple of the known value of e, proceed to get data on more drops, working with each one as long as possible, and analyzing the data after each droplet is finished. Try to observe several with the shortest free-fall time (largest radius) you can measure accurately in order to have a good basis for extrapolating your values of e.

Air currents can be a problem in this experiment. Take care that the chamber is well sealed, and reduce as much as possible any movement of air in the room.

If you are working alone you may find the following procedure more convenient:

l. Pull the droplet above the top line by adjusting the voltage;

2. Switch the voltage to zero and measure the time to fall from the top to the bottom line of the reticle. Keep your left hand on the timer controls and your right hand on the voltage controls;

3. After the droplet has passed the bottom line arrest the downward motion by switching on the voltage;

4. Read and record the fall time, taking care that you will be able to identify the droplet after you have looked away for a moment to read and record the clock;

5. Measure and record the voltage that renders the droplet exactly stationary (ν=0);

6. Pull the droplet up and above the top line;

7. Repeat the sequence many times to reduce the random errors of the time and voltage measurements.

Tabulate your data in a format that will allow you to reduce it in an orderly fashion in adjacent columns.

You will find that it takes a considerable amount of practice to achieve high accuracy in this experiment. Both members of a team should perfect their skill at making all the various measurements. The more droplets you measure and the more data you accumulate on each droplet, the more accurate will be your final result.

REPORT SHEET

EXPERIMENT 1: MILLIKAN'S OIL DROP EXPERIMENT

Student's Name:
Experiment Date:
Group Member Name(s):
Laboratory Bench Number:
Assistant's Name and Signature:

Data and Calculations

Table 1.1

V$_{stop}(V)$	x(m)	t(s)	$v_t (= x/t)(m/s)$	$q = 2x10^{-10} v_t^{3/2}/V_{stop}(C)$

Constants For Our Apparatus:

ρ ; density of oil = 800 kg/m^3
ρ'; density of air =1.29 kg/m^3
η ; viscosity of air = 1.827x10$^{-5} Ns/m^2$

For each droplet find the value of v and q and the errors. Plot $cv^{3/2}$ against V. Determine the slope (ne), and errors by linear regression. A linear fit program can be used for this purpose. From these results compute e and the errors. Take special care in understanding and evaluating the random and systematic errors.

Questions

1. Calculate the constant value in Equation (3).

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2. What is viscosity and how can it be measured?

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3. What is Stoke's law, and how can you verify it?

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4. Quarks have charges of $\pm(1/3)e$ and $\pm(2/3)e$. What is the explanation for the fact that such charges have never been observed?

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5. In the oil drop experiment a capacitor is used with a plate separation of 2.5 mm. A droplet is observed falling without electric field through a distance of 1.00 mm in 25.3 s. When a potential difference of 154.8 V raises the same droplet, it travels a distance of 1.00 mm in 18 second. The density of the oil is given as $\rho = 920 kg/m^3$, the viscosity of air as η = 1.827 x $10^{-5} Ns/m^2$. How large is the electric charge on the droplet?

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Discussion

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Chapter 2

e/m FROM ELECTRIC AND MAGNETIC DEFLECTION

Purpose

To measure the ratio of charge/mass (e/m), for electrons and to learn about phenomena of electric and magnetic deflection and application of vector product.

Introduction

In electric discharges through gases at low pressure there are observed cathode (or negative) rays and positive rays, both of which are found to be corpuscular (discrete particle). The ratio charge/mass, e/m, of these corpuscles gives evidence of their nature.

Electric and Magnetic Deflection

An electric discharge tube consists of two spherical glass bulbs connected through a narrow neck (Figure 2.1). The discharge is produced in the right bulb between the anode (the plate connected with the positive terminal of a power supply) and the cathode (the cylinder occupying the neck, connected with the negative terminal). A power supply provides several thousands or tens of thousands of volts. The gas consists, for example, of hydrogen or mercury vapor at a pressure of a few thousandths of a millimeter of mercury. A discharge fills the whole right bulb uniformly with dim light. Furthermore, a straight ray, brighter than the discharge, emanates from the front surface of the cathode, crosses the bulb, and produces fluorescence of the opposite glass surface. This ray is called a "cathode ray." An obstacle placed in its path casts a shadow on the glass surface and so demonstrates that the ray emanates from the cathode.

The nature of this ray is revealed when a magnet is brought nearby. Even the weak magnetic field surrounding a steel magnet causes a deflection. Its direction indicates that the cathode ray consists of negatively charged particles. This is confirmed when the ray is allowed to pass through the space between two parallel metal plates connected to a battery. The electric

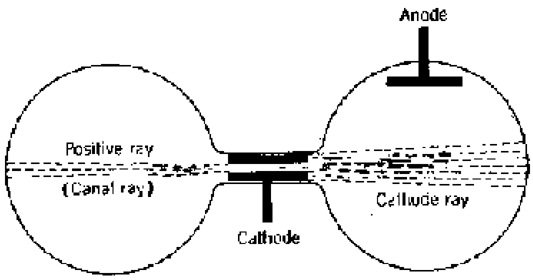

Figure 2.1: Electric Discharge

field between the metal plates deflects the cathode ray in a direction that indicates that negative charges are coming from the cathode.

A quantitative study of the deflections caused by magnetic and electric fields was made by J. J. Thomson. By way of introduction let us review the forces exerted on electric charges by such fields.

1. The electric field E between plane plates of a capacitor (distance s) connected with a battery of electromotive force V is $E = V/s$. The force exerted by this field E on the charge e is Ee; it is directed parallel to E.

2. A wire of length l carrying a current I when placed in a magnetic field directed perpendicular to the wire is acted upon by a force equal to IlB, where B is magnetic induction. The direction of this force is perpendicular to that of the wire and that of the magnetic field.

Applying this basic law to the cathode ray, which consists of n electrons per meter of length moving with velocity v, we obtain

Current = nev

so that

Force on length $l = nevlB$

where nl = number of electrons contained in l. Hence

Force on one electron = evB

Again the force is perpendicular to both v and B.

For his quantitative study of the magnetic and electric deflections Thomson, in 1897, applied uniform fields limited to a well-defined space.

A schematic diagram is given in Figure 2.2. The electric discharge through a gas at low pressure takes place in the left part of the tube. The cathode ray hits the anode, which consists of a metal plate with a small hole at its center. This transmits a narrow section of the cathode ray into the right part of the tube. There the ray is no longer subjected to the strong electric field acting between cathode and anode.

The field-free space is better understood when it is assumed that the whole inside glass surface on the right side of the anode is covered by a conducting layer. Thus the inside is free of electric fields everywhere except between the capacitor plates to be described presently.

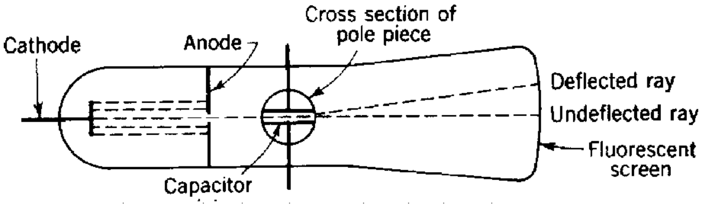

Figure 2.2: Electric and magnetic deflection of a cathode ray

Beyond the perforated anode the ray continues its path with uniform velocity in a straight line except in the limited space indicated in the diagram where a vertical electric field may be applied between a pair of capacitor plates or a magnetic field with lines of force directed out of the plane of the paper. In Figure 2.2 the circle indicates the cross section of the pole pieces. We presuppose that both these fields are uniform within a limited space and zero outside. With this arrangement the cathode ray can be deflected at will upward or downward by either the electric or the magnetic field. The cathode ray is only dimly visible, but its direction can be well demonstrated by the fluorescence it produces on the opposite glass wall.

J.J. Thomson combined the results of two consecutive measurements (subscripts 1 and 2). For the first measurement the cathode ray is deflected by a certain electric field E_1. Next, by a magnetic induction B_1, adjusted to the proper value and direction, the cathode ray is brought back into the position it had without any field. For this adjustment of the two fields the forces exerted by the one and the other field are equal and opposite. Hence,

$$E_1 e = evB_1,$$

As the fields E_1 and B_1 can be measured, he derived the velocity v as the unknown, $v = E_1/B_1$. The numerical result is a very high velocity of many thousand kilometers per second, the value depending on the conditions of the experiment, in particular the potential difference applied between cathode and anode.

In the second measurement only a magnetic induction B_2 is applied. In this case the theory predicts a circular path of the charged particles within the range of the magnetic field. Outside this field the ray travels in a straight line. The circular path is explained by the fact that the mechanical force exerted by the constant induction B on the particle of velocity v is everywhere perpendicular to the velocity. Hence, for any small element of the path, this force does not produce a change of the absolute velocity but only a uniform deflection.

This is the difference between the two fields applied in these experiments: The electric field exerts a mechanical force fixed in space; this field when applied alone bends the path of charged particles into a parabola, like the path of a bullet shot horizontally. On the other hand, the magnetic field exerts a mechanical force turning with the instantaneous velocity; this field bends the path of the charged particles into a circle.

For the circular path in the magnetic induction B_2 the following condition holds: Centripetal force (or mass x centripetal acceleration) = force exerted by the magnetic induction, or, when r = radius of curvature and m = mass of particle,

$$\frac{mv^2}{r} = evB_2$$

So weak a magnetic induction is applied that the charged particles are by no means bent into a full circle but only slightly deflected from their originally straight path. This deflection is observed on the fluorescent screen and, by a simple geometrical consideration, the radius of curvature r of their path is computed; the velocity v was determined by the first experiment. Thus there is one equation with two unknowns e and m. We derive one unknown, e/m, called the "specific charge" of the particles:

$$\frac{e}{m} = \frac{v}{rB_2} \tag{1}$$

Thomson's important result is that the specific charge of cathode-ray particles is always the same; in particular, it does not depend upon the nature of the gas or the metals contained in the apparatus. The numerical result obtained by recent measurements is

$$e/m = 1.75888 \text{ x } 10^{11} coulombs/kg$$

This result reveals the nature of the cathode ray. The ray does not consist of charged gaseous atoms; otherwise e/m would depend upon the nature of the gas. We are led to a positive statement when we compare the value of e/m with the largest value obtained for charged atoms in electrolysis, which is the value for hydrogen: 9.578 x $10^7 C/kg$. For cathode-ray particles the order of magnitude is much larger, 1,836 times the value obtained for charged hydrogen atoms in electrolysis. Should this large value of e/m be interpreted as a large value of the charge e or a small value of the mass m? The answer can only be guessed as follows: The electrolysis found that all charged atoms carry the same fundamental electric charge or small multiples of it. Their values of e/m, however, differ because the masses differ. It may be inferred that for cathode-ray particles, too, the charge is the same, presumably the fundamental charge. Then the large value of e/m must be attributed to a small mass, of magnitude only 1/1,836 that of the hydrogen atom. This excessively small value indicates that here the particles are fundamentally different from the atoms known in chemistry.

Thomson concluded that the cathode ray consists of free electricity and thus gives evidence of free electrons.

In these experiments the free electrons are always observed as negatively charged particles, while in electrolysis some atoms carry positive, others negative charges. Recognizing the negative charge as an essential property of free electricity, we come to a new interpretation of charged atoms: Positively charged atoms have lost one or several electrons from their neutral structure. Negatively charged atoms have gained electrons.

A certain variation in e/m is attributed to different masses m. This implies that the charge e considered a constant. Throughout physics, including nuclear physics, the conservation of electric charge, which here is assumed, is a principle never violated.

The constancy of e/m of electrons, consistently measured with six significant figures, fails only for very high speed. For example, electrons accelerated by 80,000V are observed to have a speed of 1.5 x $10^8 m/s$ (one-half of the velocity of light) and a specific charge e/m about one-eighth smaller than the standard value.

Electric Acceleration and Magnetic Deflection

Next we shall describe an alternative determination of e/m of free electrons. In 1883, T. A. Edison, during the development of the incandescent lamp, discovered that glowing filaments of carbon or metal give off electricity. This is demonstrated by an incandescent lamp which carries inside the evacuated glass bulb a metal plate, insulated from the glowing filament and supported by a wire which is sealed through the glass. When the plate is made positive with respect to the filament, a current flows through the vacuum and is registered on a sensitive meter. There is no current flow when the plate is made negative.

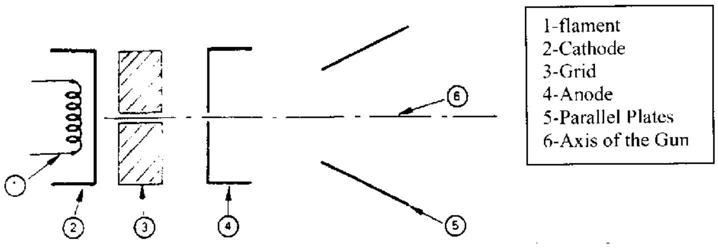

Figure 2.3: Electron Gun

The nature of this current is explored by the following experiment (Figure 2.3). A straight glowing filament F is mounted along the axis of a small metal cylinder A, insulated from the cylinder. This cylinder and filament are placed a very low residual pressure of mercury vapor. When the filament is heated and made negative with respect to the cylinder, a current flows from the filament to the cylinder. A narrow slit along the wall of the cylinder, parallel to its axis, transmits a narrow ray of electric charges coming from the filament, shooting out in a straight direction. As in Thomson's experiment, the space outside the slit is free of electric fields. The whole glass bulb is placed between coils of wire so constructed that the electric current through the wire produces a uniform magnetic field perpendicular to the direction of the ray described. When this field is turned on, the ray is bent in a circular path of which the radius r is easily measured. While in Thomson's experiment, shown in Figure 2.2, the low-pressure gas is essential for the production of the ray of electrons by processes to be discussed later, in the experiment of Figure 2.3, the negatively charged particles are emitted from the glowing filament irrespective of the presence of the gas. Here the gas has only the auxiliary purpose of making visible the path of the otherwise invisible ray of charged particles.

What is the nature of the particles that constitute the ray? They are negatively charged as they are pulled to the positively charged cylinder. Their specific charge e/m is determined by the measurement of the accelerating voltage (between filament and cylinder) and the magnetic field. To begin with, the kinetic energy T of the charged particles (charge e; mass m) hitting the plate under the effect of potential difference $\triangle V$ is computed. By definition the potential V is correlated with the electric field E by the

$$E \cos\theta = -\frac{dV}{ds}$$

where θ is the angle between the direction of E and the arbitrarily selected path element ds. (A positive charge is driven by the field to regions of lower potential.) When a positively charged body (charge q) is accelerated by the field along the distance $\triangle s$, it picks up the kinetic energy

$$T = q \text{ x (field component) x } \triangle s = \text{-}q \triangle V$$

to the electron by where $\triangle V$ is negative. Hence the total energy given the transit from one electrode (potential V_a) to another (potential V_b) is

$$T = \frac{1}{2}mv^2 = \textstyle\int_{V_a}^{V_b} edV = e \triangle V$$

Next the effect of the magnetic induction B is represented by the same argument as applied to Thomson's experiment:

$$\frac{mv^2}{r} = evB \tag{2}$$

Equations (1) and (2) contain two unknowns, v and e/m. These are expressed in terms of measurable quantities as follows:

$$v = \frac{2 \triangle V}{Br}$$

and

$$\frac{e}{m} = \frac{2 \triangle V}{B^2 r^2}$$

The numerical result of the measurement is $e/m = 1.759 \text{ x } 10^{11} C/kg$. Here we recognize the same particles identified earlier by Thomson as free electrons. The reader is familiar with the great technical importance of electron emission from glowing filaments, as applied in radio tubes.

The previous statement that glowing filaments give off only negatively charged particles is not accurate. Occasionally, there is also observed a weak emission of positively charged particles, which are detected only when the polarity of the glowing filament with respect to the plate is reversed so that free electrons cannot reach the plate. By the determination of e/m of these positive particles it has been found that they consist of positive ions, usually of sodium and chemically related metals. This emission of positive ions is limited to filaments carrying impurities. After a short period of time the supply is exhausted, and the positive current stops-unlike the current of the opposite polarity, the electron current, which is never exhausted. The emission of positive ions is of minor importance.

Let us compare the two methods for the determination of the specific charge e/m of electrons. Thomson's original method has the advantage of applying to any well-defined ray of charged particles, irrespective of its origin. This method is indispensable for the investigation of alpha rays and beta. Because these rays are emitted from radioactive atoms, it is not possible to accelerate them, starting from zero velocity. On the other hand, the acceleration of electrons from a filament combined with magnetic deflection is of great practical importance in numerous laboratory experiments performed with glowing filaments. After discussing the charge on the electron, we shall see that this method provides a new unit of energy, the electron volt, which is commonly used in atomic physics.

Helmholtz Coils

Consider a circular loop of wire carrying a current I (Figure 2.4). The magnetic field produced such a circuit at an arbitrary point is very difficult to compute; however, if only points on the axis of symmetry are considered, the expression for B is relatively simple.

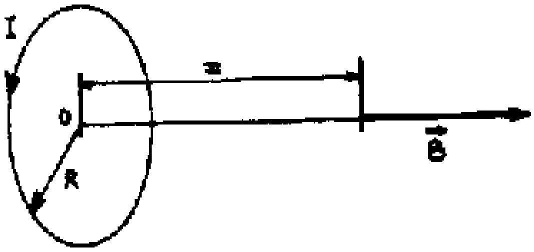

Figure 2.4:

The field at point x;

$$B = \frac{\mu_o R^2 I}{2(R^2 + x^2)^{3/2}} \qquad\qquad \mu_o = 4\pi 10^{-7} H/m \quad \text{in SI}$$

B is entirely along the x axis. A frequently used current configuration is the Helmholtz coil, which consist of two circular coils of the same radius, with a common axis, separated by a distance, R. The magnetic induction at the midpoint is

$$B = \frac{2\mu_o R^2 NI}{2(R^2 + x^2)^{3/2}}$$

Since $x = R/2$, $\qquad B = \frac{8\mu_o NI}{5^{3/2} R} = 7.8 \text{ x } 10^{-4} I$ for our coils.

Helmholtz coils play an important role in scientific research, where they are frequently used to produce a relatively uniform magnetic field over a small region of space.

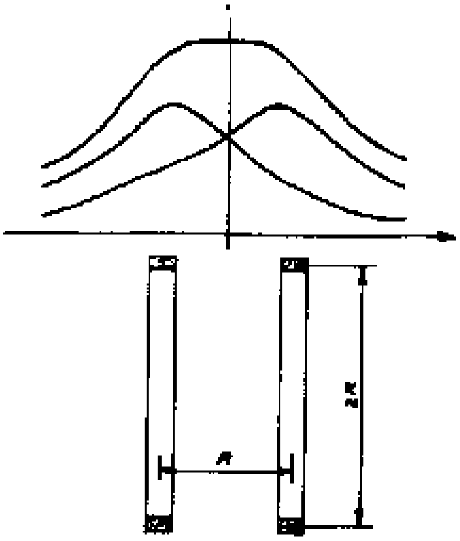

Figure 2.5: Helmholtz Coils

Procedure

Part 1: Electromagnetic Deflection

The obvious reason for this experiment's existence is to allow you to check your understanding of the magnetic force on a charged particle. The general equation for this force is the *Lorentz force law*:

$F_B = qvxB$

This equation tells you that the magnetic force on a charged particle is perpendicular to both the magnetic field and the velocity. You can use this rule, along with the knowledge that electrons have negative charge, to figure out the direction of the magnetic field inside the Helmholtz coils. In the special case of a particle moving perpendicular to a uniform magnetic field, it is easy to see that this leads to a circular orbit. The acceleration is perpendicular to the velocity and so will change only its direction, and since v and B are both constant the magnitude of the acceleration will also be uniform. This lets us equate the magnetic force with the centripetal acceleration:

$$ev_eB = v_e^2/R$$

Part 2: Electrostatic Deflection

This is another method of getting at the e/m value for the electron. If the Helmholtz coils are off and a potential difference V_d is put across the parallel plates, then the electrons moving through the cathode ray tube are affected by a "constant" electric field and so experience a "constant" force. Over the region of the grid this is very close to true, but outside the grid the field weakens. This may affect your results significantly and is worth investigating. Turn the switch to the "electrical deflection" position to observe a deflection.

Since the electrons are experiencing a constant force, they travel just like projectiles fired from a cannon. This lets you write down the x and y coordinates as a function of the force, initial velocity, and time:

$$x = v_et \tag{1}$$

$$y = a_yt^2/2 = (F_E/m)t^2/2 \tag{2}$$

The time can be substituted for any x-coordinate by rewriting Equation (1) as $t = x/v_e$. The force on the electron is just eE, and the electric field is just V_d/D, where D is the distance between the plates. We can take that last step only because the field is uniform (this was an issue in electric lab). Combining all this information into Equation (2) gives us:

$$y = (e/m)(V_d/D)(x/v_e)^2/2 \tag{3}$$

Part 3: Determination of e/m by Magnetic Deflection

Turn the switch to the "e/m measure" position to observe a circular orbit. Keep accelerating voltage at $200V$. Apply bias to the Helmholtz coils. Measure the radius of electron's orbit for various magnetic field intensities. Fill the Table 2.1.

REPORT SHEET

EXPERIMENT 2: e/m FROM ELECTRIC AND MAGNETIC DEFLECTION

Student's Name:
Experiment Date:
Group Member Name(s):
Laboratory Bench Number:
Assistant's Name and Signature:

Data and Calculations

Table 2.1

I(A)	r(m)	B(T)	V(V)	$1/r^2$	B^2
0.9			200		
1.0					
1.1					
1.2					
1.3					
1.4					
1.5					
1.6					

In Part 1, if you increase the velocity of the electrons by turning up the accelerating voltage, you should see the radius of the trajectory increase proportionally. Do you see a helix or circular orbit? What is the difference between them? Find the direction of magnetic field.

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In Part 2, we will only observe electric deflection without taking any data. Draw deflection of electrons. After reversing the bias, what do you see?

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Those of you who have thought of some sources of error already can take heart; discuss them in you lab report for a better grade. If your best value for e/m is inconsistent with the known value, you can look at each source and see whether it could cause the kind of offset which you found in your data. We haven't listed all the sources of systematic error here for you because it's important to learn how to find them yourself.

Plot $1/r^2$ versus B^2, find its slope, calculate e/m and compare it with the results given in Physics Handbook.

Questions

1. Is it possible to find your direction by use of a cathode ray tube, electron gun or an osscilloscope? If it is possible, explain how you can perform it?

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2. In an experiment a cathode ray passes between plates 1 cm apart, connected with a power supply of 790V; the electrostatic deflection is compensated by a magnetic induction of 3x10$^{-3}Wb/m^2$. In a second experiment the same cathode ray is bent by a magnetic induction of 1.250x10$^{-3}Wb/m^2$ into a circular path of 12.00 cm radius. Compute e/m of the cathode-ray particles.

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3. *Electric acceleration and magnetic deflection.* Electrons are accelerated from a glowing filament toward a plate by a potential difference of 100 V. After passing through a slit, they enter a space free of electric fields in which they are subjected to a magnetic induction of 3.00x10$^{-4}Wb/m^2$ directed perpendicular to their velocity. Find their linear velocity v beyond the slit and the radius R of their path in the magnetic field.

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Discussion

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Chapter 3

ELECTRON DIFFRACTION

Purpose

The purpose of the experiment is to observe the wave behaviour of particles (electrons) from diffraction and to determine the interplanar spacings in graphite.

Introduction

In 1924, Louis de Broglie proposed that matter, just like light, has a dual character behaving in some circumstances like particles and in others like waves.

In 1927 Davisson and Germer in the United States and G.P. Thomson in England independently confirmed the existence of de Broglie waves, and demonstrated that the electron beams are diffracted, when they are scattered by the regular atomic arrays of crystals. G.P. Thomson used a monoenergetic beam of electrons through a thin metal target foil. The target was not a single large crystal (as in the Davisson and Germer experiment), but was made up of a large number of tiny, randomly oriented crystallises. With this arrangement, there will always, by chance, be a certain number of crystallises oriented at the proper angle to produce a diffracted beam.

It is well known that a photon of light of frequency ν has the momentum

$p = h\nu/c$

To explain in the interference phenomenon, a wavelength λ which depends on momentum, is assigned to the electrons in accordance with the de Broglie equation:

$$\lambda = \frac{h}{p} \tag{1}$$

where h = 6.625 x $10^{-34} Js$, Planck's constant.

The momentum can be calculated from the velocity that the electrons acquire under acceleration voltage U$_A$:

$$\frac{1}{2}mv^2 = \frac{p^2}{2m} = eU_A \tag{2}$$

The wavelength is thus

$$\lambda = \frac{h}{\sqrt{2meU_A}} \tag{3}$$

where

$e = 1.602$ x $10^{-19} As$ (the electron charge) and

$m = 9.109$ x $10^{-31} kg$ (rest mass of electron).

Since our apparatus is operated below 10 kV, the electrons are non-relativistic. Relativistic corrections are not required for the above relations.

At the voltages U_A used, the relativistic mass can be replaced by the rest mass with an error of only 0.5%.

The electron beam strikes a polycrystalline graphite film deposite on a copper grating and is reflected in accordance with the Bragg condition:

$$2d\sin\theta = n\lambda, \quad n = 1,2,... \tag{4}$$

where d is the spacing between the planes of the carbon atoms and θ is the Bragg angle (angle between electron beam and lattice planes).

In polycrystalline graphite, the bond between the individual layers (Figure 3.1) is broken so that their orientation is random. The electron beam is therefore spread out in the form of a cone and produces interference rings on the fluorescent screen.

The Bragg angle θ can be calculated from the radius of the interference ring but it should be remembered that the angle of deviation α (Figure 3.2) is twice as great:

$$\alpha = 2\theta$$

From Figure 3.2 we read off

$$\sin 2\alpha = \frac{r}{R} \tag{5}$$

where $R = 65$ mm, radius of the glass bulb. Now,
$\sin 2\alpha = 2\sin\alpha\cos\alpha$

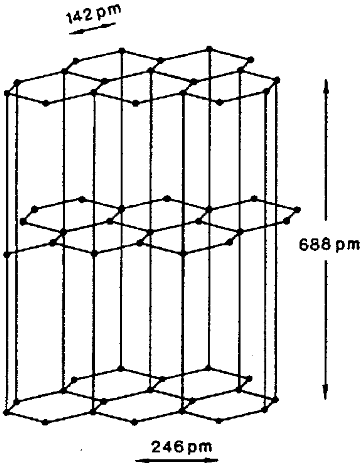

Figure 3.1: Crystal lattice of graphite

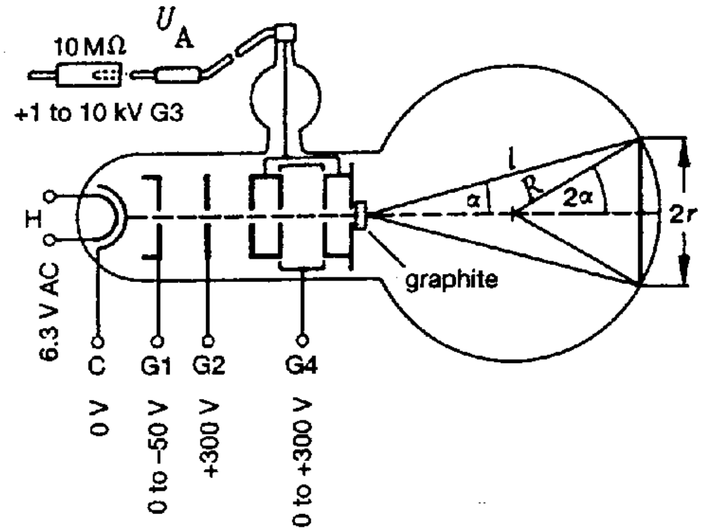

Figure 3.2: Setup and Power Supply to the Electron Diffraction Tube

For small angles α ($\cos 10^o = 0.985$) can put

$$\sin 2\alpha \cong 2 \sin \alpha \tag{6}$$

so that for small angles θ we obtain

$$\sin \alpha = \sin 2\theta \cong 2 \sin \theta \tag{6a}$$

With this approximation we obtain

$$r = \frac{2R}{d} n\lambda \tag{7}$$

The two inner interference rings occur through reflection from the lattice planes of spacing d_1 and d_2 (Figure 3.3), for $n = 1$ in Equation (7).

Related Topics:

Bragg reflection, Debye-Scherrer method, lattice planes, graphite structure, material waves, de Broglie equation.

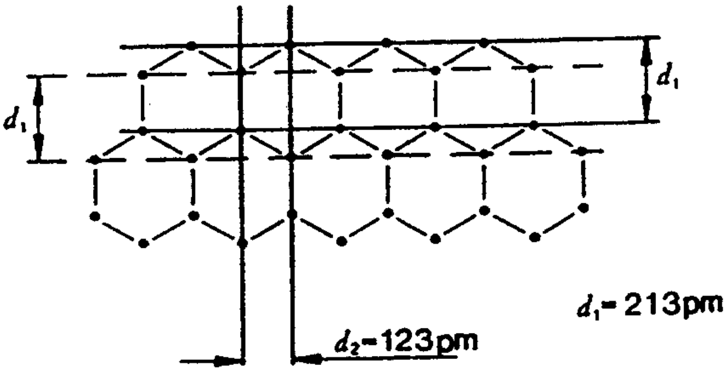

Figure 3.3: Graphite planes for the first two interference rings

Equipments

Electron diffr. tube a. mounting
High voltage supply unit, 0-10 kV
High-value resistor, 10 MΩ
Connecting cord, 50 KV, 500 mm
Power supply, 0 ... 600 VDC
Vernier caliper, plastic

Procedure

1. Set up the experiment as shown in Figure 3.4. Connect the sockets of the electron diffraction tube to the power supply as shown in Figure 3.5. Connect the high voltage to the anode G3 through a 10 MΩ protective resistor.

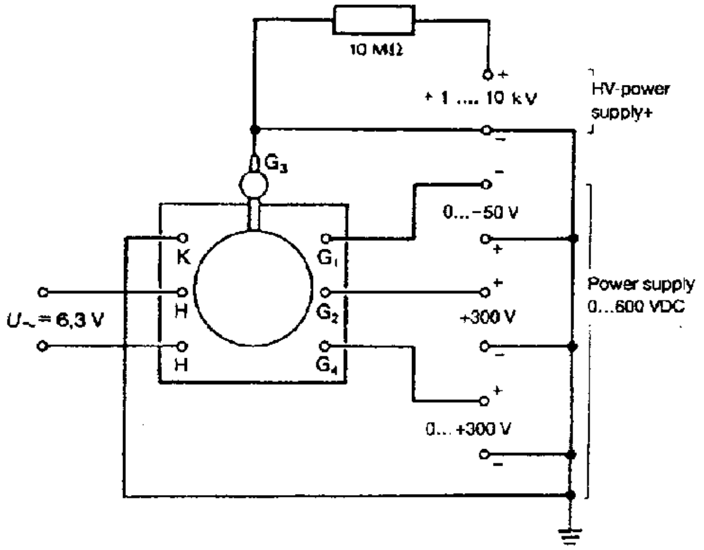

Figure 3.4: Experimental set-up: electron diffraction

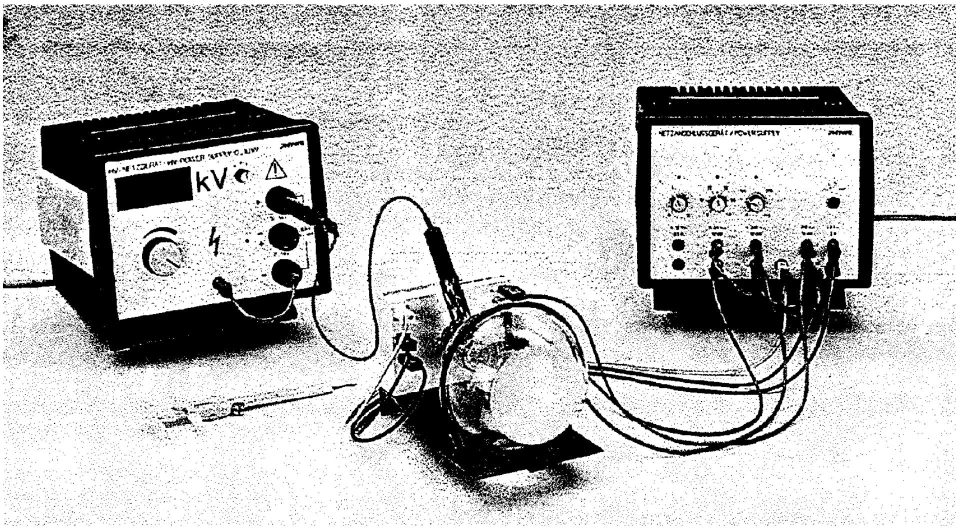

Figure 3.5:

2. Set the Wehnelt voltage Gl and the voltages at grid G4 and G3 so that sharp well defined diffraction rings appear. Read the anode voltage at the display of the HV power supply.

3. To determine the diameter of the diffraction rings, measure the inner and outer edge of the rings with the vernier caliper (in a darkened room) and take an average. Note that there is another faint ring immediately behind the second ring.

Notes:

- The intensity of higher order interference rings is much lower than that of first order rings. Thus, for example, the second order ring of d_1 is difficult to identify and the expected fourth order ring of dl simply cannot be seen. The third order ring of d_1 is easy to see because graphite always has two lattice planes together, spaced apart by a distance of $d_{1/3}$ (Figure 3.6)

In the sixth ring, the first order of ring of d4 clearly coincides with the second order one of d_2.

- The visibility of high order rings depends on the light intensity in the laboratory and the contrast of the ring system which can be influenced by the voltages applied to G1 and G4.

- The bright spot just in the center of the screen can damage the fluorescent layer of the tube. To avoid this reduce the light intensity after each reading as soon as possible.

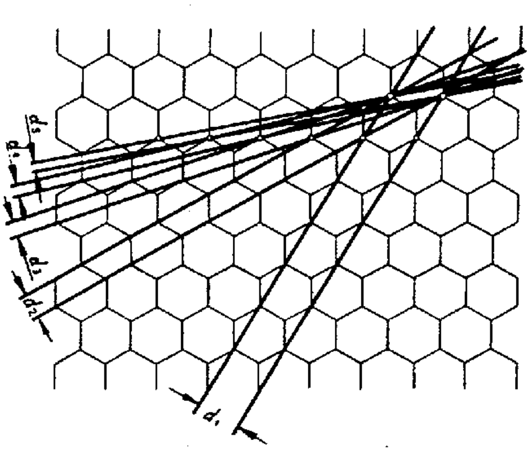

Figure 3.6: Interplanar spacing in grapite, d_1=213 pm, d_2=123 pm, d_3=80.5 pm, d_4=59.1 pm, d_5=46.5 pm

REPORT SHEET

EXPERIMENT 3: ELECTRON DIFFRACTION

Student's Name:
Experiment Date:
Group Member Name(s):
Laboratory Bench Number:
Assistant's Name and Signature:

Data and Calculations

Table 3.1

U_A (kV)	λ(pm)	r_{1in}(mm)	r_{1out}(mm)	r_{1ave}(mm)	r_{2in}(mm)	r_{2out}(mm)	r_{2ave}(mm)
4.00							
4.50							
5.00							
5.50							
6.50							
7.00							
7.40							

Calculate the wavelength from the anode voltage in accordance with Equation (3).

For two interference rings plot r versus λ, use linear fit to find its slope. Calculate lattice constants.

Questions

1. What is the de Broglie wavelength of electrons of an energy 20 000 eV in the beam of a TV tube? Is classical mechanics likely to be a satisfactory approximation for the operation of TV tubes?

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2. A beam of electrons of energy 64.0 eV is incident on an aluminyum foil containing many microcrystals. The interface pattern produced by the scattered beams is observed on a

fluorescent screen placed 15.0 cm beyond the foil. The pattern consist of several concentiric circles. Calculate the radii of the circles that result from Bragg reflections by a set of planes with a spacing of 4.04 Angstrom.

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3. An electron moves along a circular path 0.5 cm in radius in a uniform magnetic field of strength H = 46 oe. What is the de Broglie wavelength of the electron?

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4. Calculate the theoretical magnitude of the resolving power to be expected in an electron microscope when an accelerating voltage of 100 kV is applied. What will be the de Broglie wavelength of the electrons be in this case?

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Discussion

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Chapter 4

THERMAL RADIATION SYSTEM

Introduction

The Thermal Radiation System includes three items: the Radiation Sensor, the Radiation Cube (Leslie's Cube), and the Stefan-Boltzmann Lamp. This manual contains operating instructions for each of these items plus instructions and worksheets for the following four experiments:

1. Introduction to Thermal Radiation
2. Inverse Square Law
3. Stefan-Boltzmann Law* (at high temperatures)
4. Stefan-Boltzmann Law* (at low temperatures)

Radiation Sensor

The Radiation Sensor (Figure 4.1) measures the relative intensifies of incident thermal radiation. The sensing element, a miniature thermopile, produces a voltage proportional to the intensity of the radiation. The spectral response of the thermopile is essentially flat in the infrared region (from 0.5 to 40 μm), and the voltages produced rance from the microvolt range up to around 100 millivolts. (A good millivolt meter is sufficient for all the experiments described in this manual.

The Sensor can be hand held or mounted on its stand for more accurate positioning. A spring-clip shutter is opened and closed by sliding the shutter ring forward or back. During experiments, the shutter should be closed when measurements are not actively being taken. This helps reduce temperature shifts in the thermopile reference junction which can cause the sensor response to drift.

Note: When opening and closing the shutter, it is possible you may inadvertently change the sensor position. Therefore, for experiments in which the sensor position is critical, two small sheets of opaque insulating foam have been provided. Place this heat shield in front of the sensor when measurements are not actively being taken.

The two posts extending from the front end of the Sensor protect the thermopile and also provide a reference for positioning the sensor a repeatable distance from a radiation source.

Specifications

Temperature Range: -65 to 85 ^{o}C
Maximum Incident Power: 0.1 $Watts/cm^2$
Spectral Response: .6 to 30 μm
Signal Output: Linear from 10^{-6} to $10^{-1} Watts/cm^2$

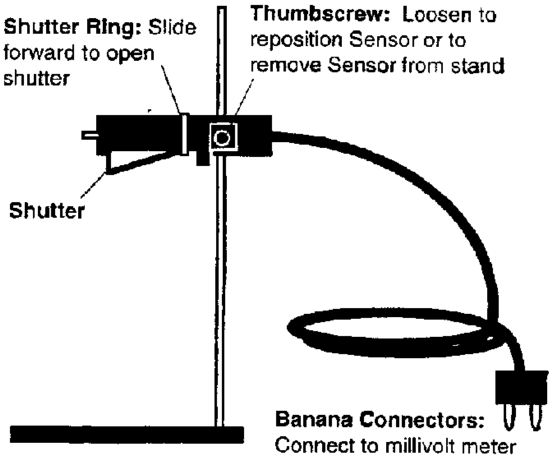

Figure 4.1: Radiation Sensor

Radiation Cube

The Radiation Cube (Figure 4.2) provides four different radiating surfaces that can be heated from room temperature to approximately 120 ^{o}C. The cube is heated by a 100 watt light bulb. Just plug in the power cord, flip the toggle switch to "ON", then turn the knob clockwise to vary the power.

Measure the cube temperature by plugging, your ohmmeter into the banana plug connectors labeled THERMISTOR. The thermistor is embedded in one corner of the cube. Measure the resistance, then use Table 4.1, below, to translate the resistance reading into a temperature measurement. An abbreviated version of this table is printed on the base of the Radiation Cube.

Note: For best results, a digital ohmmeter should be used.

Table 4.1 Resistance versus Temperature for the Thermal Radiation Cube

Term. R(Ω)	T(°C)	Term. R(Ω)	T(°C)	Term. R(Ω)	T(°C)	Term. R(Ω)	T(°C)
207.850	10	39.605	46	10.110	82	3.215.8	118
197.560	11	37.995	47	9.767.2	83	3.123.0	119
187.840	12	36.458	48	9.437.7	84	3.033.3	120
178.650	13	34.991	49	9.120.8	85	2.946.5	121
169.950	14	33.591	50	8.816.0	86	2.862.5	122
161.730	15	32.253	51	8.522.7	87	2.781.3	123
153.950	16	30.976	52	8.240.6	88	2.702.7	124
146.580	17	29.756	53	7.969.1	89	2.626.6	125
139.610	18	28.590	54	7.707.7	90	2.553.0	126
133.000	19	27.475	55	7.456.2	91	2.481.7	127
126.740	20	26.409	56	7.214.0	92	2.412.6	128
120.810	21	25.390	57	6.980.6	93	2.345.8	129
115.190	22	24.415	58	6.755.9	94	2.281.0	130
109.850	23	23.483	59	6.539.4	95	2.218.3	131
104.800	24	22.590	60	6.330.8	96	2.157.6	132
100.000	25	21.736	61	6.129.8	97	2.098.7	133
95.447	26	20.919	62	5.936.1	98	2.041.7	134
91.126	27	20.136	63	5.749.3	99	1.986.4	135
87.022	28	19.386	64	5.569.3	100	1.932.8	136
83.124	29	18.668	65	5.395.6	101	1.880.9	137
79.422	30	17.980	66	5.228.1	102	1.830.5	138
75.903	31	17.321	67	5.066.6	103	1.781.7	139
72.560	32	16.689	68	4.910.7	104	1.734.3	140
69.380	33	16.083	69	4.760.3	105	1.688.4	141
66.356	34	15.502	70	4.615.1	106	1.643.9	142
63.480	35	14.945	71	4.475.0	107	1.600.6	143
60.743	36	14.410	72	4.339.7	108	1.558.7	144
58.138	37	13.897	73	4.209.1	109	1.518.0	145
55.658	38	13.405	74	4.082.9	110	1.478.6	146
53.297	39	12.932	75	3.961.1	111	1.440.2	147
51.048	40	12.479	76	3.843.4	112	1.403.0	148
48.905	41	12.043	77	3.729.7	113	1.366.9	149
46.863	42	11.625	78	3.619.8	114	1.331.9	150
44.917	43	11.223	79	3.513.6	115		
43.062	44	10.837	80	3.411.0	116		
41.292	45	10.467	81	3.311.8	117		

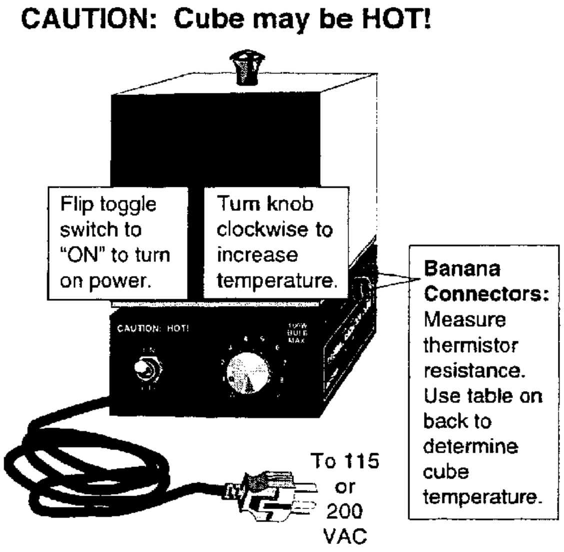

Figure 4.2: Radiation Cube (Leslie's Cube)

Stefan-Boltzmann Lamp

Important: The voltage into the lamp should NEVER exceed 13 V. Higher voltages will burn out the filament.

The Stefan-Boltzmann Lamp (Figure 4.3) is a high temperature source of thermal radiation. The lamp can be used for high temperature investigations of the Stefan-Boltzmann Law. The high temperature simplifies the analysis because the fourth power of the ambient temperature is neglicibly small compared to the fourth power of the high temperature of the lamp filament. When properly oriented, the filament also provides a good approximation to a point source of thermal radiation. It therefore works well for investigations into the inverse square law.

By adjusting the power into the lamp (13 Volts max, 2 A min, 3 A max), filament temperatures up to approximately 3,000 ^{o}C can be obtained. The filament temperature is determined by carefully measuring the voltage and current into the lamp. The voltage divided by the current gives the resistance of the filament.

For small temperature changes, the temperature of the tungsten filament can be calculated using α, the temperature coefficient of resistivity for the filament:

$$T = \frac{R - R_{ref}}{\alpha R_{ref}} + T_{ref}$$

where,
T = Temperature
R = Resistance at temperature T
T_{ref} = Reference temperature (usually room temp.)

R_{ref} = Resistance at temperature T_{ref}
α = Temperature coefficient of resistivity for the filament ($\alpha = 4.5 \text{ x}10^{-3}K^{-1}$ for tungsten)

For large temperature differences, however, α is not constant and the above equation is not accurate. For large temperature differences, therefore, determine the temperature of the tungsten filament as follows:

1. Accurately measure the resistance (R_{ref}) of the tungsten filament at room temperature (about 300 K). Accuracy is important here. A small error in R_{ref} will result in a large error in your result for the filament temperature.

2. When the filament is hot, measure the voltage and current into the filament and divide the voltage by the current to measure the resistance (R_T).

3. Divide R_T by R_{ref} to obtain the relative resistance (R_T/R_{ref}).

4. Using your measured value for the relative resistivity of the filament at temperature T, use Table 4.2 , or the associated graph, to determine the temperature of the filament.

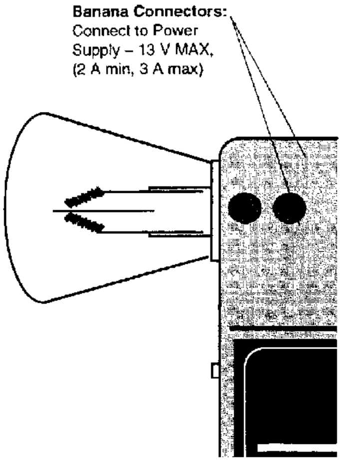

Figure 4.3: Stefan-Boltzmann Lamp

Table 4.2 Temperature and Resistivity for Tungsten

R/R_{300K}	Temp(K)	$Resistivity(\mu\Omega\ cm)$
1.0	300	5.65
1.43	400	8.06
1.87	500	10.56
2.34	600	13.23
2.85	700	16.09
3.36	800	19.00
3.88	900	21.94
4.41	1000	24.93
4.95	1100	27.94
5.48	1200	30.98
6.03	1300	34.08
6.58	1400	37.19
7.14	1500	40.36
7.71	1600	43.55
8.28	1700	46.78
8.86	1800	50.05
9.44	1900	53.35
10.03	2000	56.67
10.63	2100	60.06
11.24	2200	63.48
11.84	2300	66.91
12.46	2400	70.39
13.08	2500	73.91
13.72	2600	77.49
14.34	2700	81.04
14.99	2800	84.70
15.63	2900	88.33
16.29	3000	92.04
16.95	3100	95.76
17.62	3200	99.54
18.28	3300	103.3
18.97	3400	107.2
19.66	3500	111.1
26.35	3600	115.0

The Stefan-Boltzmann Law, for the high temperatures relates R, the power per unit area radiated by an object, to T, the absolute temperature of the object. The equation is:

$R = \sigma T^4 \qquad (\sigma = 5.6703 \text{ x } 10^{-8} W/m^2K^4)$

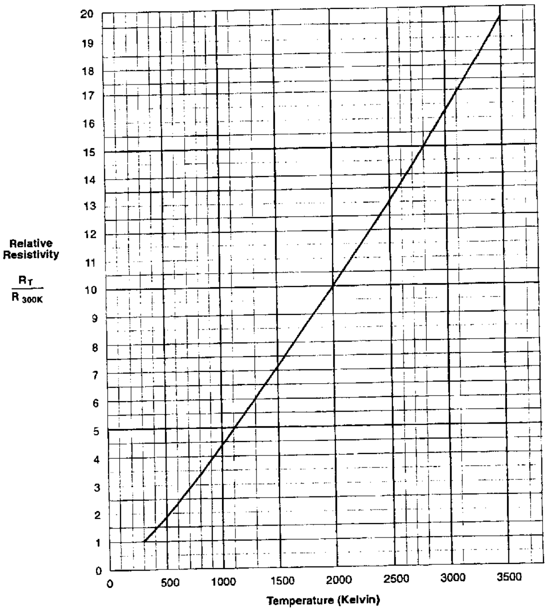

Figure 4.4: Temperature versus Resistivity for Tungsten

You will make relative measurements of the power per unit area emitted from a hot object, namely the Stefan-Boltzmann Lamp, at various temperatures. From your data you will be able to test whether the radiated power is really proportional to the fourth power of the temperature.

Most of the thermal energy emitted by the lamp comes from the filament of the lamp. The filament temperature can be determined using the procedure given in this manual.

At high temperatures (approximately 1000 to 3000 K), the ambient temperature is small enough that it can be neglected in the analysis. When you will investigate the Stefan-Boltzmann relationship at much lower temperatures using the Thermal Radiation Cube, you will see that at these lower temperatures, the ambient temperature can not be ignored.

If the detector in the Radiation Sensor were operating, at absolute zero temperature, it would produce a voltage directly proportional to the intensity of the radiation that strikes it. However, the detector is not at absolute zero temperature so it is also radiating, thermal energy. According to the Stefan-Boltzmann law, it radiates at a rate, $R_{det} = \sigma T_{det}^4$. The voltage produced by the sensor is proportional to the radiation striking the detector minus the radiation leaving it. Mathematically, the sensor voltage is proportional to $R_{net} = R_{rad} - R_{det} = \sigma(T^4 - T_{det}^4)$. As long as you are careful to shield the Radiation Sensor from the Radiation Cube when measurements are not being taken, T_{det} will be very close to room temperature (T_{rm}).

Procedure

Experiment 1: Introduction To Thermal Radiation

Equipments

Radiation Sensor
Thermal Radiation Cube
Window glass
Millivoltmeter
Ohmmeter

Notes:

1. If lab time is short, it's helpful to preheat the cube at a setting of 5.0 for 20 minutes before the laboratory period begins. (A very quick method is to preheat the cube at full power for 45 minutes, then use a small fan to reduce the temperature quickly as you lower the power input. Just be sure that equilibrium is attained with the fan off.)

2. Part 1 and 2 of this experiment can be performed simultaneously. Make the measurements in Part 2 while waiting for the Radiation Cube to reach thermal equilibrium at each of the settings in Part 1.

3. When using the Radiation Sensor, always shield it from the hot object except for the few seconds it takes to actually make the measurement. This prevents heating of the thermopile which will change the reference temperature and alter the reading.

Radiation Rates from Different Surfaces

Part 1

1. Connect the Ohmmeter and Millivoltmeter as shown in Figure 4.5.

2. Turn on the Thermal Radiation Cube and set the power switch to "HIGH". Keep an eye on the ohmmeter reading. When it gets down to about 40 kΩ, reset the power switch to 5.0. (If the cube is preheated, just set the switch to 5.0.)

3. When the cube reaches thermal equilibrium the ohmmeter reading will fluctuate around a relatively fixed value-use the Radiation Sensor to measure the radiation emitted from each of the four surfaces of the cube. Place the Sensor so that the posts on its end are in contact with the cube surface (this ensures that the distance of the measurement is the same for all surfaces). Record your measurements in Table 4.3. Also measure and record the resistance of the thermistor. Use the table on the base of the cube to determine the corresponding temperature.

4. Increase the power switch setting, first to 6.5, then to 8.0, then to "HIGH". At each setting, wait for the cube to reach thermal equilibrium, then repeat the measurements of step 1 and record your results in the appropriate table.

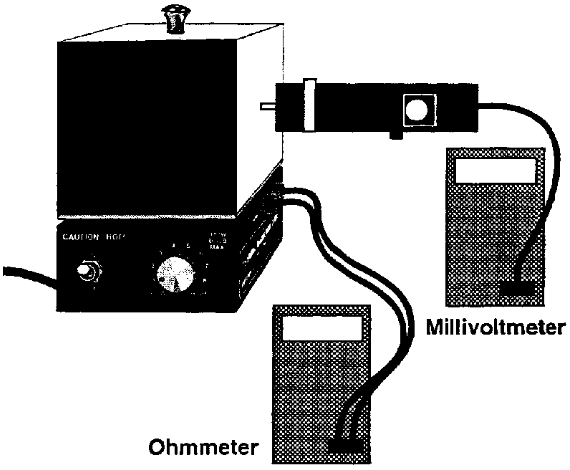

Figure 4.5: Equipment Setup

Part 2

Use the Radiation Sensor to examine the relative magnitudes of the radiation emitted from various objects around the room. On a separate sheet of paper, make a table summarizing your observations. Make measurements that will help you to answer the questions.

Absorption and Transmission of Thermal Radiation

1. Place the Sensor approximately 5 cm from the black surface of the Radiation Cube and record the reading. Place a piece of window glass between the Sensor and the bulb. Does window glass effectively block thermal radiation?

2. Remove the lid from the Radiation Cube (or use the Stefan-Boltzmann Lamp) and repeat the measurements of step 1, but using the bare bulb instead of the black surface. Repeat with other materials.

Experiment 2: Inverse Square Law

Equipments

Radiation Sensor
Stefan-Boltzmann Lamp,
Millivoltmeter
Power Supply (12 VDC; 3 A), meter stick.

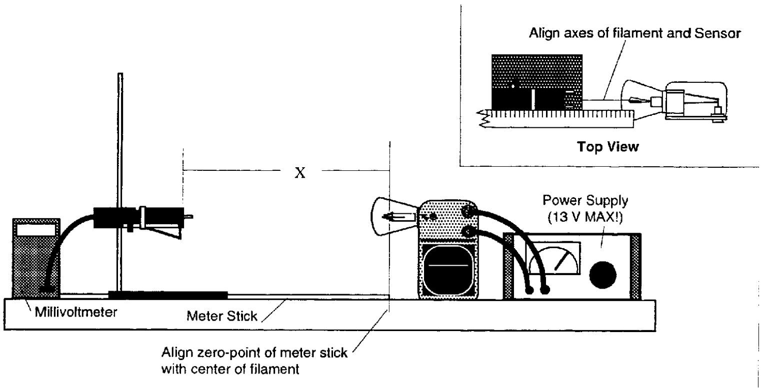

Figure 4.6: Equipment Setup

1. Set up the equipment as shown in Figure 4.6.

a. Tape a meter stick to the table.

b. Place the Stefan-Boltzmann Lamp at one end of the meter stick as shown. The zero-point of the meter stick should align with the center of the lamp filament.

c. Adjust the height of the Radiation Sensor so it is at the same level as the filament of the Stefan-Boltzmann Lamp.

d. Align the lamp and sensor so that, as you slide the Sensor along the meter stick, the axis of the lamp aligns as closely as possible with the axis of the Sensor.

e. Connect the Sensor to the millivoltmeter and the lamp to the power supply as indicated in the figure.

2. With the lamp OFF, slide the sensor along the meter stick. Record the reading of the millivolt-meter at 10 cm intervals. Record your values in Table 4.5. Average these values to determine the ambient level of thermal radiation. You will need to subtract this average ambient value from your measurements with the lamp on, in order to determine the contribution from the lamp alone.

3. Turn on the power supply to illuminate the lamp. Set the voltage to approximately 10 V.

4. Adjust the distance between the Sensor and the lamp to each of the settings listed in Table 4.4. At each setting, record the reading on the millivoltmeter.

Important: Do not let the voltage to the lamp exceed 13V.

Make each reading quickly. Between raedings, move the Sensor away from the lamp or place the reflective heat shield between the lamp and the Sensor, so that the temperature of the Sensor stays relatively constant.

Experiment 3: Stefan-Boltzmann Law (High Temperature)

Equipments

Radiation Sensor
Stefan-Boltzmann Lamp
Ohmmeter , Ammeter (0-3 A)
Voltmeter (0-12 V) , Millivoltmeter
Thermometer

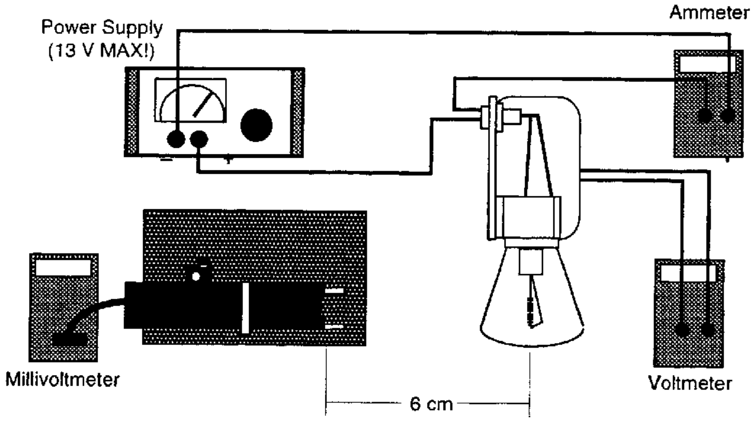

Figure 4.7: Equipment Setup

1. BEFORE TURNING ON THE LAMP, measure T_{ref}, the room temperature in degrees Kelvin, ($K =^o C + 273$) and R_{ref}, the resistance of the filament of the Stefan-Boltzmann Lamp at room temperature. Record your results.

2. Set up the equipment as shown in Figure 4.7. The voltmeter should be connected directly to the binding posts of the Stefan-Boltzmann Lamp. The Sensor should be at the same height as the filament, with the front face of the Sensor approximately 6 cm away from the filament. The entrance angle of the thermopile should include no close objects other than the lamp.

3. Turn on the power supply. Set the voltage, V, to each of the settings listed in Table 4.6. At each voltage setting, record I, the ammeter reading, and Rad, the reading on the millivoltmeter.

Important: The voltage into the lamp should never exceed 13 V. Higher voltages will burn out the filament.

Make each Sensor reading quickly. Between readings, place both sheets of insulating foam between the lamp and the Sensor, with the silvered surface facing the lamp, so that the temperature of the Sensor stays relatively constant.

Experiment 4: Stefan-Boltzmann Law (Low Temperature)

Equipments

Radiation Sensor
Thermal Radiation Cube
Millivoltmeter
Ohmmeter

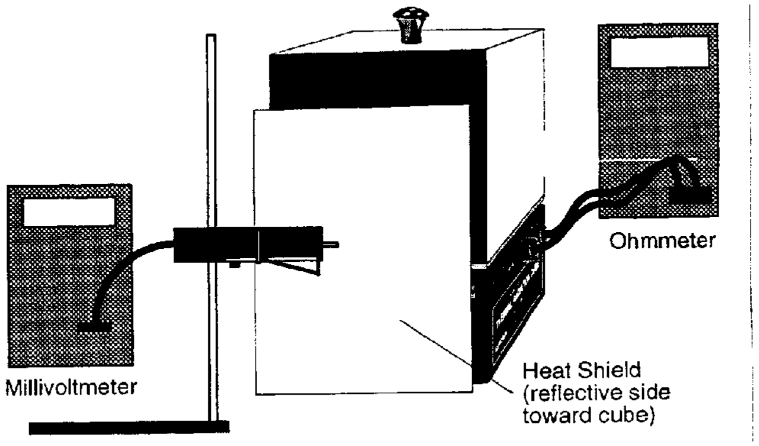

Figure 4.8: Equipment Setup

1. Set up the equipment as shown in Figure 4.8. The Radiation Sensor should be pointed directly at the center of one of the better radiating surfaces of the cube (the black or white surface). The face of the Sensor should be parallel with the surface of the cube and about 3 to 4 cm away.

2. With the Thermal Radiation Cube off, measure R_{rm}, the resistance of the thermistor room temperature. Record this data.

3. Shield the sensor from the cube using the reflecting heat shield, with the reflective side of the shield facing the cube.

4. Turn on the Radiation Cube and set the power switch to 10.

5. When the thermistor resistance indicates that the temperature is about 12 ^{o}C above room temperature, turn the power down so the temperature is changing slowly. Read and record R, the ohmmeter reading, and Rad, the millivoltmeter reading. The readings should be taken as nearly simultaneously as possible while briefly removing the heat shield. Record these values in Table 4.7.

6. Replace the heat shield, and turn the cube power to 10. When the temperature has risen an additional 12-15^o C, repeat the measurements of step 5. Repeat this procedure at about 12-15^o C intervals until the maximum temperature of the cube is reached.

Important: Make each reading quickly, removing the heat shield only as long as it takes to make the measurement. Take care that the position of the sensor with respect to the cube is the same for all measurements.

REPORT SHEET

EXPERIMENT 4: THERMAL RADIATION SYSTEM

Student's Name:
Experiment Date:
Group Member Name(s):
Laboratory Bench Number:
Assistant's Name and Signature:

Data and Calculations

Experiment 1: Introduction To Thermal Radiation

Radiation Rates From Different Surfaces

Table 4.3

Power Setting 5.0
Therm. Res.——————-Ω
Temperature——————-^oC

Surface	Sensor Reading (mV)
Black	
White	
Polished Al	
Dull Al	

Power Setting 6.5
Therm. Res.——————-Ω
Temperature——————-^oC

Surface	Sensor Reading (mV)
Black	
White	
Polished Al	
Dull Al	

Power Setting 8.0
Therm. Res.——————-Ω
Temperature——————-^oC

Surface	Sensor Reading (mV)
Black	
White	
Polished Al	
Dull Al	

Power Setting 10.0
Therm. Res.——————-Ω
Temperature——————-^oC

Surface	Sensor Reading (mV)
Black	
White	
Polished Al	
Dull Al	

Questions (Part 1)

1. List the surfaces of the Radiation Cube in order of the amount of radiation emitted. Is the order independent of temperature?

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2. It is a general rule that good absorbers of radiation are also good emitters. Are your measurements consistent with this rule? Explain.

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Questions (Part 2)

1. Do different objects, at approximately the same temperature, emit different amounts of radiation?

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2. Can you find materials in your room that block thermal radiation? Can you find materials that don't block thermal radiation? (For example, do your clothes effectively block the thermal radiation emitted from your body?)

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Questions (Absorption and Transmission of Thermal Radiation)

1. What do your results suggest about the phenomenon of heat loss through windows?

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2. What do your results suggest about the Greenhouse Effect?

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Experiment 2: Inverse Square Law

Table 4.4 Radiation Level versus Distance

x(cm)	Rad(mV)	$1/x^2(cm^{-2})$	Rad-Ambient(mV)
2.5			
3.0			
3.5			
4.0			
4.5			
5.0			
6.0			
7.0			
8.0			
9.0			
10.0			
12.0			
14.0			
16.0			
18.0			
20.0			
25.0			
30.0			
35.0			
40.0			
45.0			
50.0			
60.0			
70.0			
80.0			
90.0			
100.0			

Table 4.5 Ambient Radiation Level

x(cm)	Ambient Radiation Level(mV)
10	
20	
30	
40	
50	
60	
70	
80	
90	
100	

Average Ambient Radiation Level =............................

1. For each value of x, calculate $1/x^2$. Enter your results in Table 4.4.

2. Subtract the Average Ambient Radiation Level from each of your Rad measurements in Table 4.4. Enter your results in the table.

3. On a separate sheet of paper, make a graph of Radiation Level versus Distance from Source, using columns one and four from Table 4.4. Let the radiation level be the dependent (y) axis.

4. If your graph from step 3 is not linear, make a graph of Radiation Level versus $1/x^2$, using columns three and four from Table 4.4.

Questions

1. Which of the two graphs is more linear? Is it linear over the entire range of measurements?

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2. The inverse square law states that the radiant energy per unit area emitted by a point source of radiation decreases as the square of the distance from the source to the point of detection. Does your data support this assertion?

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3. Is the Stefan-Boltzmann Lamp truly a point source of radiation? If not, how might this affect your results? Do you see such an effect in the data you have taken?

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Experiment 3: Stefan-Boltzmann Law (High Temperature)

$\alpha = 4.5 \text{ x } 10^{-3} K^{-1}$

T_{ref}(room temp.) = ...K

R_{ref}(filament resistance at T_{ref}) = ...Ω

Table 4.6

Data			Calculations		
V(V)	I(A)	Rad(mV)	R(Ω)	T(K)	$T^4(K^4)$
1.00					
2.00					
3.00					
4.00					
5.00					
6.00					
7.00					
8.00					
9.00					
10.00					
11.00					
12.00					

1. Calculate R, the resistance of the filament at each of the voltage settings used ($R = V/I$). Enter your results in Table 4.6.

2. Use the procedure in this manual to determine T, the temperature of the lamp filament at each voltage setting. Enter your results in the table.

3. Calculate T^4 for each value of T and enter your results in the table.

4. On a separate sheet of paper, construct a graph of Rad versus T^4. Use Rad as your dependent variable (y-axis).

In place of calculations 3 and 4, some may prefer to perform a power regression on Rad versus T to determine their relationship, or graph on log-log, paper and find the slope.

Questions

1. What is the relationship between Rad and T? Does this relationship hold over the entire range of measurements?

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2. The Stefan-Boltzmann Law is perfectly true only for ideal, black body radiation. A black body is any object that absorbs all the radiation that strikes it. Is the filament of the lamp a true black body?

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3. What sources of thermal radiation, other than the lamp filament, might have influenced your measurements? What affect would you expect these sources to have on your results?

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Experiment 4: Stefan-Boltzmann Law (Low Temperature)

Room Temperature:

R_{rm} =...............Ω
T_{rm} =.............^oC =.............K

Table 4.7

Data Calculations

R()	Rad(mV)	T_c(^{o}C)	T_k(K)	T_k^4(K^4)	T_k^4-T_{rm}^4(K^4)

1. Using the table on the base of the Thermal Radiation Cube, determine T_c, the temperature in degrees Centigrade corresponding to each of your thermistor resistance measurements. For each value of T_c, determine T_k, the corresponding value in degrees Kelvin ($K =^o C + 273$). Enter both sets of values in Table 4.7. In the same manner, determine the room temperature, T_{rm}.

2. Calculate T_k^4 for each value of T_k and record the values in the table.

3. Calculate T_k^4 - T_{rm}^4 for each value of T_k and record your results in the table.

4. On separate sheet of paper, construct a graph of Rad versus T_k^4 - T_{rm}^4. Use Rad as the dependent variable (y-axis).

Questions

1. What does your graph indicate about the Stefan-Boltzmann law at low temperatures?

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2. Is your graph a straight line? Discuss any deviations that exist.

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Discussion

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Chapter 5

THE PHOTOELECTRIC EFFECT

Purpose

The purpose of this experiment is to demostrate the particle behavior of light and determine Planck's constant h.

Introduction

The emission and absorption of light was an early subject for investigation by German physicist Max Planck. As Planck attempted to formulate a theory to explain the spectral distribution of emitted light based on a classical wave model, he ran into considerable difficulty. Classical theory (Rayleigh-Jeans Law) predicted that the amount of light emitted from a black body would increase dramatically as the wavelength decreased, whereas experiment showed that it approached zero. This discrepancy became known as the ultraviolet catastrophe.

Experimental data for the radiation of light by a hot, glowing body showed that the maximum intensity of emitted light also departed dramatically from the classically predicted values (Wien's Law). In order to reconcile theory with laboratory results, Planck was forced to develop a new model for light called the quantum model. In this model, light is emitted in small, discrete bundles or quanta.

The relationship between the classical and quantum theories for the emission of light can be investigated using the scientific h/e Apparatus. Using the apparatus, in combination with the Mercury Vapor Light Source allows an accurate determination of the h/e ratio and thus a deternination of h, Planck's constant.

Planck's Quantum Theory

By the late 1800's many physicists thought they had explained all the main principles of the universe and discovered all the natural laws. But as scientists continued working, inconsistencies that couldn't easily be explained began showing up in some areas of study.

In 1901 Planck published his law of radiation. In it he stated that an oscillator, or any similar physical system, has a discrete set of possible energy values or levels; energies between these values never occur.

Planck went on to state that the emission and absorption of radiation is associated with transitions or jumps between two energy levels. The energy lost or gained by the oscillator is emitted or absorbed as a quantum of radiant energy, the magnitude of which is expressed by the equation:

$E = h\nu$

where E equals the radiant energy, ν is the frequency of the radiation, and h is a fundamental constant of nature. The constant, h, became known as Planck's constant.

Planck's constant was found to have significance beyond relating the frequency and energy of light, and became a cornerstone of the quantum mechanical view of the subatomic world. In 1918, Planck was awarded a Nobel prize for introducing the quantum theory of light.

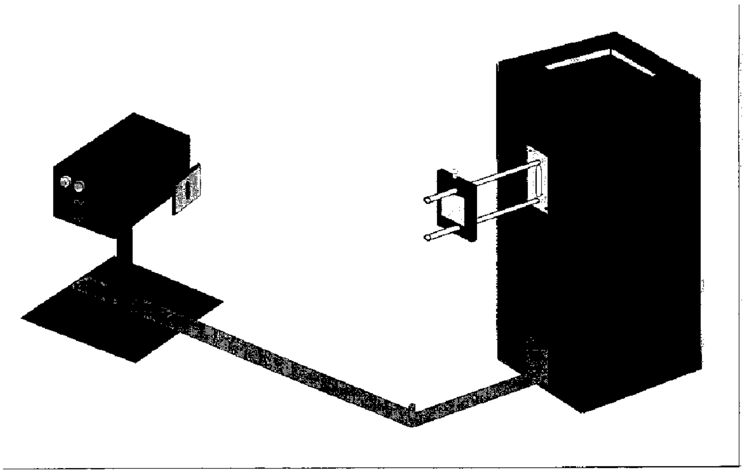

Figure 5.1: The h/e Apparatus Shown With the Accessory Kit and Mercury Vapor Light Source

The Photoelectric Effect

In photoelectric emission, light strikes a material, causing electrons to be emitted. The classical wave model predicted that as the intensity of incident light was increased, the amplitude and thus the energy of the wave would increase. This would then cause more energetic photoelectrons to be emitted. The new quantum model, however, predicted that higher frequency light would produce higher energy photoelectrons, independent of intensity, while increased intensity would only increase the number of electrons emitted (or photoelectric current). In the early 1900s several investigators found that the kinetic energy of the photoelectrons was dependent on the wavelength, or frequency, and independent of intensity, while the magnitude of the photoelectric current, or number of electrons was dependent on the intensity as predicted by the quantum model. Einstein applied Planck's theory and explained the photoelectric effect in tenns of the quantum model using his famous equation for which he received the Nobel prize in 1921:

$$E = h\nu = KE_{max} + W_o$$

where KE_{max} is the maximum kinetic energy of the emitted photoelectrons; and W_o is the energy needed to remove them from the surface of the material (the work function). E is the energy supplied by the quantum of light known as a photon.

The h/e Experiment

A light photon with energy $h\nu$ is incident upon an electron in the cathode of a vacuum tube. The electron uses a minimum W_o of its energy to escape the cathode, leaving it with a maximum energy of KE_{max} in the form of kinetic energy. Normally the emitted electrons reach the anode of the tube, and can be measured as a photoelectric current. However, by applying a reverse potential V between the anode and the cathode, the photoelectric current can be stopped. KE_{max} can be determined by measuring the minimum reverse potential needed to stop the photoelectrons and reduce the photoelectric current to zero.* Relating kinetic energy to stopping potential gives the equation:

$$KE_{max} = eV$$

Therefore, using Einstein's equation,

$$h\nu = eV + W_o$$

When solved for V, the equation becomes:

$$V = (h/e)\nu - (W_o/e)$$

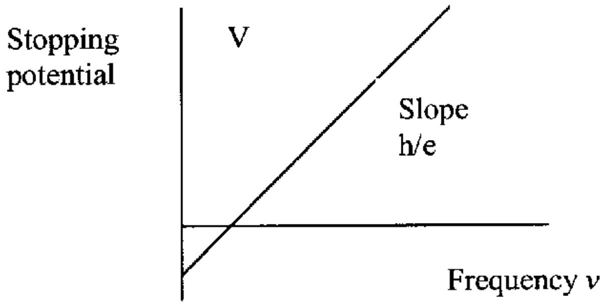

Figure 5.2: gragh

If we plot V versus ν for different frequencies of light, the graph will look like Figure 5.2. The V intercept is equal to, W_o/e and the slope is h/e. Coupling our experimental determination of the ratio h/e with the accepted value for e, 1.602 x 10^{-19} coulombs, we can determine Planck's constant, h.

The Mercury Vapor Light Source

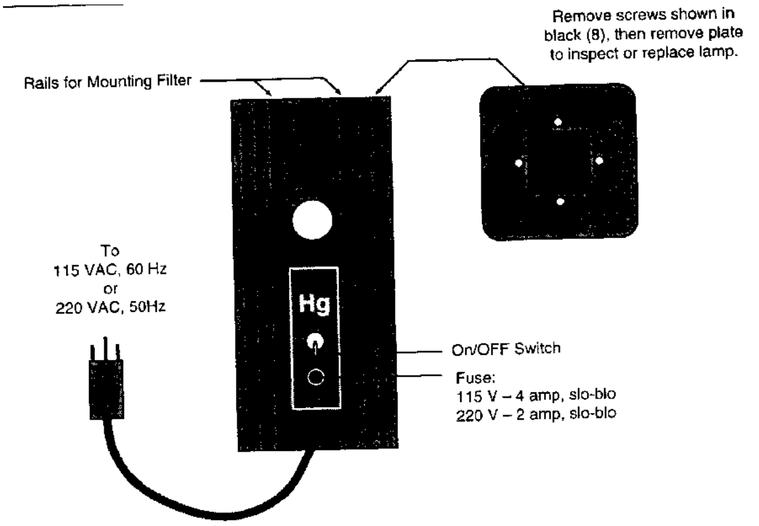

Figure 5.3: Mercury Vapor Light Source

The Mercury Vapor Light Source provides approximately 3,000 lumens of light in the mercury spectrum. The 100 watt light source comes ready to use, with a built-in power supply. Cooling fins and air vents on the sturdy aluminum case ensure cool, safe operation. In addition, rails on the front and rear of the case can be used for mounting standard 2-inch by 2-inch filters, so that monochromatic light can be obtained.

Note: For maximum life of the mercury vapor lamp:

1. Always operate the light source in its upright position.

2. If you are going to use the light source more than once during the day, leave it on. Lamp wear results more from turning the light source on and off than from steady operation.

Table Wavelength of the Mercury Spectral Lines

Color	Frequency (Hz)	Wavelength (nm)
Yellow	5.18672E+14	578
Green	5.48996E+14	546.074
Blue	6.87858E+14	435.835
Violet	7.40858E+14	404.656
Ultraviolet	8.20264E+14	365.483

Note: The yellow line is actually a doublet with wavelengths of 578 and 580 nm.

Caution I: The outer glass tube of the mercury vapor lamp blocks hartnful ultraviolet radiation produced by the lamp. If the outer tube is cracked or broken, this radiation can

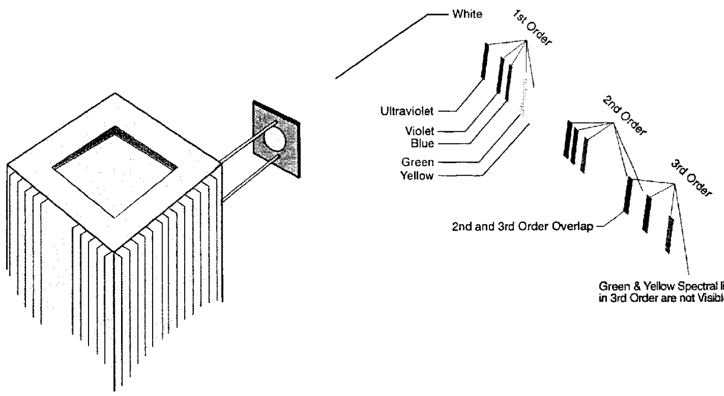

Figure 5.4: The Three Orders of Light Gradients

cause severe skin bum and produce eye inflammation. Regularly inspect the outer tube for cracks, especially if the light source has received a significant jolt. If the glass bulb is broken, immediately turn lamp off and remove it to avoid possible injury. Replace Bulb prior to next use.

Caution II: Do not open the light source with the unit plugged in.

Note: The grating is blazed to produce the brightest spectrum on one side only. During your experiment, you may need to turn the Lens/Grating Assembly around in order to have the brightest spectrum on a convenient side of your lab table.

Note: The white reflective mask on the h/e apparatus is made of a special fluorescent material. This allows you to see the ultraviolet line as a blue line, and it also makes the violet fine appear more blue. You can see the actual colors of the light if you hold a piece of white non-fluorescent material in front of the mask. (the palm of your hand works in a pinch, although it fluoresces enough, that UV line will still be visible.)

When making measurements it is important that, only one color falls on the photodiode window. There must be no overlap from adjacent spectral maxima.
Note: For some apparatus, the stopping potential will temporarily read high and then drop down to the actual stopping potential voltage.

Using the Filters

The h/e Apparatus includes three filters: one green and one yellow, plus a variable transmission filter. The filter frames have magnetic strips and mount to the outside of the white reflective mask of the h/e Apparatus.

Use the green and yellow filters when you're using the green and yellow spectral lines. These filters limit higher frequencies of light from entering the h/e apparatus. This prevents ambient room light from interfering with, the lower energy yellow and green light and masking the true, results. It also blocks the higher frequency ultraviolet light from the higher order spectra which may overlap with lower orders of yellow and green.

The Variable Transmission Filter consists of computer generated patterns of dots and lines that vary the intensity (not the frequency) of the incident light. The relative transmission percentages are 100%, 80%, 60%, 40%, and 20%.

Equipments

h/e Apparatus
h/e Apparatus Accessory Kit
Mercury Vapor Light Source
Digital voltmeter

Procedure

1. Set up the equipment as shown in the Figure 5.1. Focus the light from the Mercury Vapor Light Source onto the slot in the white reflective mask on the h/e Apparatus. Tilt the Light, Shield of the Apparatus out of the way to reveal the white photodiode mask inside the, Apparatus. Slide the Lens/Grating assembly forward and back on its support rods until you achieve the sharpest image of the aperture centered on the hole in the photodiode mask. Secure the Lens/Grating by tightening the thumbscrew.

2. Align the system by rotating the h/e Apparatus on its support base so that the same color light that falls on the opening of the light screen falls on the window in the photodiode mask, with no overlap of color from other spectral lines. Return the Light Shield to its closed position.

3. Check the polarity of the leads from your digital voltmeter (DVM), and connect them to the OUTPUT terminals of the same polarity on the h/e Apparatus.

Experiment 1: The Wave Model of Light vs. the Quantum Model

According to the photon theory of light, the maximum kinetic energy, KE_{max} of photoelectrons depends only on the frequency of the incident light, and is independent of the intensity. Thus the higher the frequency of the light, the greater its energy.

In contrast, the classical wave model of light predicted that KE_{max} would depend on light intensity. In other words, the brighter the light, the greater its energy.

This lab investigates both of these assertions. Part A selects two spectral lines from a mercury light source and investigates the maximum energy of the photoelectrons as a function of the intensity. Part B selects different spectral lines and investigates the maximum energy of the.photoelectrons as a function of the frequency of the light.

Part A

1. Adjust the h/e Apparatus so that only one of the spectral colors falls upon the opening of the mask of the photodiode. If you select the green or yellow spectral line, place the corresponding colored. filter over the White Reflective Mask on the h/e Apparatus

2. Place the Variable Transmission Filter in front of the White Reflective Mask (and over the colored filter, if one is used) so that the light passes through the section marked 100% and reaches the photodiode. Record the DVM voltage reading in the table below.

Press the instrument discharge button, release it, and observe approximately how much time is required to return to the recorded voltage.

3. Move the Variable Transmission Filter so that the next section is directly in front of the incoming light. Record the new DVM reading, and approximate time to recharge after the discharge button has been pressed and released.

Repeat Step 3 until you have tested all five sections of the filter.
Repeat the procedure using a second color from the spectrum.

Part B

1. You can easily see five colors in the mercury light spectrum. Adjust the h/e Apparatus so that only one of the yellow colored bands falls upon the opening, of the mask of the photodiode. Place the yellow colored filter over the White Reflective Mask on the h/e Apparatus.

2. Record the DVM voltage reading (stopping potential) in the table below.

3. Repeat the process for each color in the spectrum. Be sure to use the green filter when measuring the green spectrum.

Note: While the impedance of the zero gain amplifier is very high ($\uparrow 10^{13}$) is not infinite and some charge leaks off. Thus charging the apparatus is analogous to filling a bath tub with different water flow rates while the drain is partly open.

Experiment 2: The Relationship between Energy, Wavelength and Frequency

According to the quantum model of light, the energy of light is directly proportional to its frequency. Thus, the higher the frequency, the more energy it has. With careful experimentation. the constant of proportionality, Planck's constant, can be determined.

In this lab you will select different spectral lines from mercury and investigate the maximum energy of the photoelectrons as a function of the wavelength and frequency of the light.

1. You can see five colors in two orders of the mercury light spectrum. Adjust the h/e Apparatus carefully so that only one color from the first order (the brightest order) falls on the opening of the mask of the photodiode.

2. For each color in the first order, measure the stopping potential with the DVM and record that measurement in the table below. Use the yellow and green colored filters on the Reflective Mask of the h/e Apparatus when you measure the yellow and green spectral lines.

3. Move to the second order and repeat the process. Record your results in the table below.

REPORT SHEET

EXPERIMENT 5: THE PHOTOELECTRIC EFFECT

Student's Name:
Experiment Date:
Group Member Name(s):
Laboratory Bench Number:
Assistant's Name and Signature:

Data and Calculations

Part A

Experiment 1: The Wave Model of Light vs. the Quantum Model

Table 5.1

Color # 1	% Transmission	Stopping Potential	Approx. Charge Time
	100		
	80		
	60		
	40		
	20		
Color #2	% Transmission	Stopping Potential	Approx. Charge Time
	100		
	80		
	60		
	40		
	20		

Part B

Table 5.2

Light Color	Stopping Potential
Yellow	
Green	
Blue	
Violet	
Ultraviolet	

1. Describe the effect that passing different amounts of the same colored light through the Variable Transmission Filter has on the stopping potential and thus the maximum energy of the photoelectrons, as well as the charging time after pressing the discharge button.

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2.Describe the effect that different colors of light had on the stopping potential and thus the maximum energy of the photoelectrons.

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3.Defend whether this experiment supports a wave or a quantum model of light based on your lab results.

Explain why there is a slight drop in the measured stopping potential as the light intensity is decreased.

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Experiment 2: The Relationship between Energy, Wavelength and Frequency

Table 5.3

First Order Color	Wavelength nm	Frequency x10^{14}Hz	Stopping Potential V
Yellow			
Green			
Blue			
Violet			
Ultraviolet			
Second Order Color	Wavelength nm	Frequency x10^{14}Hz	Stopping Potential V
Yellow			
Green			
Blue			
Violet			
Ultraviolet			

Determine the wavelength and frequency of each spectral line. Plot a graph of the stopping potential vs. frequency.

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Determine the slope and y-intercept. Interpret the results in terms of the h/e ratio and the W_o/e ratio. Calculate h and W_o.

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Report your values and discuss your results with an interpretation based on a quantum model for light.

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Questions

1. What is the most important statement you can made from the results of your experiment?

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2. Even if the bias voltage is zero, you can still measure a photocurrent. Explain why ?

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3 . When the anode is positive with respect to the cathode, why doesn't the current immediately rise to its saturation value? What happens to electrons which do not reach the anode?

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Discussion

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Chapter 6

MAGNETIC FIELD INSIDE A CONDUCTOR

Purpose

A current which produces a magnetic field is passed through an electrolyte. This magnetic field inside the conductor is determined as a function of the current in the conductor and of the distance from the axis of the conductor.

Introduction

The hollow cylinder (Figure 7.1) enables the magnetic field distribution inside a conductor to be investigated. In this case an electrolyte is used as the conductor. A wire gauze surrounding the hollow cylinder allows the field pattern to be determined virtually free from interference.

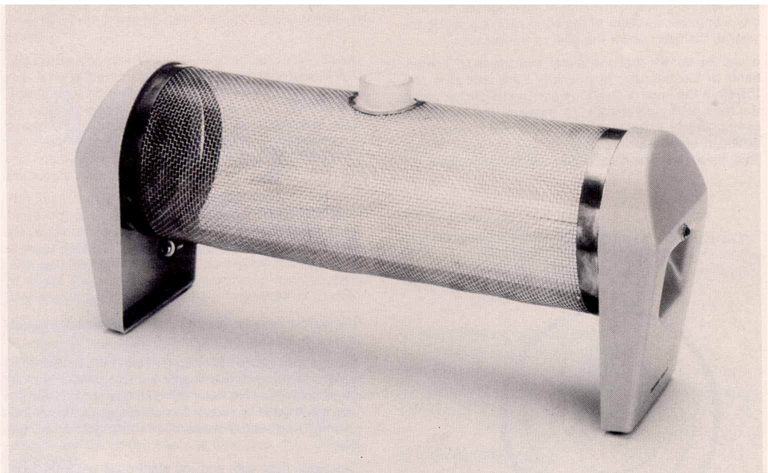

Figure 6.1:

The apparatus is particularly suitable for introducing the concepts of the magnetic field of a conductor (flux law) and the law of induction. Furthermore, it is possible to show the pattern of the magnetic lines of flux and to demonstrate the 'Right hand rule' clearly.

The liquid electrolyte (dilute hydrochloric acid) used as conductor is contained in a horizontal cylindrical plastic vessel, the metallic end faces of which constitute the electrodes. A probe can be inserted through an opening on the upper side of the vessel. To avoid polarization effects, the current passing through the electrolyte is an AC of audio frequency. In order to attain a sufficiently high sensitivity, a small test coil connected in series with a low frequency amplifier is used as the probe. The alternating voltage induced in the coil by an alternating magnetic field of frequency f is, as is known, proportional to the product fB, the same is true, then, for the amplified voltage V at the output side of the low frequency amplifier;

$$V \sim fB$$

Thus, at constant frequency, the measured voltage V is a measure of the magnetic flux density B at the probe.

The internal magnetic field of a straight conductor with uniform current density over its circular cross-section must have the same symmetry as the external field. It sufficies, therefore, to investigate the magnetic flux density along one diameter of the conductor, e.g. along the vertical diameter under the inlet of the vessel.

It can be shown that the radial and the axial components of the magnetic flux density B are both zero, and therefore the lines of flux form concentric circles about the axis of the conductor. To measure the tangential component of B, the test coil in the liquid conductor is arranged as shown in Figure 7.2 , so that the lines of flux pass through the surface of the coil at right angles.

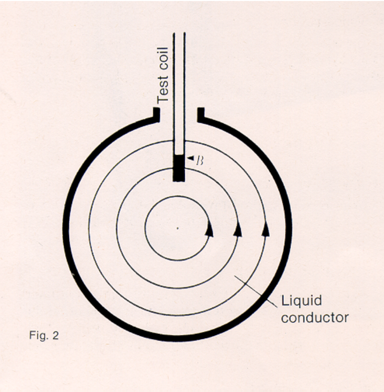

Figure 6.2:

The magnetic field of the return line causes marked disturbance, especially when measuring near the axis of the conductor. In order to keep this error small the return wire has to be laid some distance away (several meters from the liquid conductor). However, if the return current passes through the wire gauze surrounding the hollow cylinder the measurement can be carried out virtually free from interference. The wire gauze constitutes a hollow conductor with no magnetic field in its interior. Thus, the magnetic field of the current flowing through the electrolyte prevails exclusively inside the liquid conductor.

In the outer space, however, there is no resulting magnetic field present because the fields practically compensate each other owing to the opposed directions of the current in the liquid conductor and in the wire gauze hollow conductor.

To measure the tangential component of the magnetic field the search coil is adjusted so that the plane of its windings is parallel to the axis of the cylinder. By turning the test coil through 90^o (coil plane at right angles to the axis) it can be shown that no field with an axial component is present.

A conductor carrying an electric current is not only surrounded by an external magnetic field, but also has a magnetic field in its interior. The pattern of the flux density is in accordance with Maxwell's first field equation.

The induced voltage V_{ind} is

$$V_{ind} = nA\frac{dB}{dt}$$

With the number of turns n=1200 and the effective area A=74.3mm^2. Since the magnetic flux density B is produced by a sinusoidal current of frequency f or angular velocity $\omega = 2\pi f$,

$$B = B_o \ sin\omega t,$$

Therefore the induced voltage is

$$V_{ind} = nA2\pi f B_o \ sin(\omega t + \phi).$$

The phase displacement ϕ is irrelevant for this measurement. Since, according to Equation (4), the magnetic flux density is proportional to the current, the induced voltage is proportional to the current and the frequency. The current is limited by the formation of gas (electrolysis) and the frequency by the series-connected measuring instruments ($f \leq 11kHz$). The experiment was carried out at $f = 5.5kHz$ and I¡1A. The amplification was 1x10^3, position 1 is calibrated on the 10V output. The experimental set up is as shown in Figure 7.4.

Maxwell's 1st equation

$$\oint_C \vec{B} \cdot \vec{dl} = \mu_o \oint_A \vec{j} \ \vec{da}, \tag{1}$$

together with Maxwell's 4th equation

$$\int_A \vec{B} \cdot \vec{da} = 0 \tag{2}$$

gives the relationship between the steady electric current I flowing through the area A

$$I = \int_A \vec{j} \cdot \vec{da} \tag{3}$$

and the magnetic field B it produces.

C is the boundary of A
A is any given enclosed area
j is the electrical current density
μ_o is the magnetic field constant (μ_o=1.26x$10^{-6} Vs/Am$)

From Equations (1) and (2) one obtains

$$B = \frac{\mu_o I}{2\pi r} \qquad (r > R) \tag{4}$$

for a long straight conductor, where r is the distance of point P, at which the magnetic flux density is measured, from the axis of the conductor.

Since the current density j is uniform in the electrolyte, the current I flowing through the area A is expressed as a function of the current I_{tot} flowing through the whole cross-section of the electrolyte, form Equation (3) as

$$I = I_{tot} \frac{r^2}{R^2}$$

So that Equation (4) gives

$$B = \frac{\mu_o I_{tot} r}{2\pi R^2} \qquad (r \leq R) \tag{5}$$

Where R is radius of the liquid conductor.

B is measured with an induction coil. The induced voltage V is $V \sim B$.

Related Topics

Maxwell's equations, magnetic flux, induction, current density, field strength.

Details of the Apparatus

The apparatus (Figure 7.3) consists of a 'Plexiglas' cylinder 1 with copper electrodes 2 sealed across its ends. Each electrode is connected conductively to a 4mm socket 3 to which the voltage is applied.

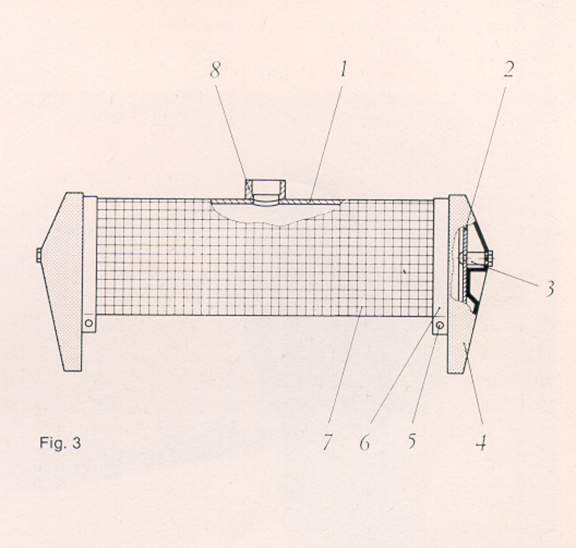

Figure 6.3:

The hollow cylinder is mounted on two non-slip plastic stands 4 provided with built-in holds.

A brass wire gauze 7 is wrapped round the hollow cylinder and secured by two copper contact strips 6 and two 4mm sockets 5; the latter are also used to connect the wire mesh into the circuit. The cut edges of the wire are sewn up and pasted over with a fabric foil to prevent injury.

The probe (test coil) and the electrolyte are introduced into the hollow cylinder through an inlet which is located in the middle of its upper side and provided with an over-flow cover 8.

Technical Data

Hollow cylinder:
Overall length 455mm
Length of the hollow space 400mm
Internal diameter 115mm
Overall height 200mm
Volume 4.2 liters

Filling neck:

Internal diameter 32mm
Height 15mm
Diameter of aperture 27mm
Electrical connections four 4mm sockets
Overall weight 1.25kg

Preparation of the Liquid

The electrolyte is prepared with due regard to safety regulations (fume cupboard, safety spectacles, rubber gloves). Approximately 200ml of 37% hydrochloric acid are poured into about 4 liters of water (not vice versa). After mixing thoroughly the electrolyte is poured into the hollow cylinder. The inlet must be left open during the experiment so that the gases which are formed (H_2 and O_2) can escape.

Assembly

The socket on one end face of the hollow cylinder is joined to the socket on the wire gauze by a short connection, so that the wire gauze provides the return circuit. The low- resistance sine-wave output of the audio-oscillator is connected through a $1A$ AC ammeter, to the corresponding sockets on the other end face. Currents of 0.7-$1A$ and frequencies of 5-$6kHz$ are appropriate.

The search coil used as the probe is plugged into a distributor and held downwards from a support stand. The depth of the probe in the liquid conductor must be variable and measureable. If the support stand is placed e.g. on an adjustable table (laboratory jack) the position of the probe in the liquid conductor can be determined by measuring the height of the table with a vertical ruler.

The test coil is connected to the input of the low frequency generator through a screened cable which should be equipped with a BNC socket/4mm plug adapter and this in turn with a connection plug with push-on sleeve; the low resistance output, to which the amplification factor of the low frequency amplifier applies, is connected to a 10V AC voltmeter.

Equipments

Hollow cylinder, Plexiglas
Search coil
Power frequency generator
LF amplifier
Digital multimeters
Adapter, BNC socket/4mm plug pair

Distributor
Meter scale $l = 1$m
Cursors 1 pair
Tripod base and barrel base
Support rod, square $l = 45$cm
Right angle clamp
Screened cable, BNC $l = 1.5$m
Hydrochloric acid

Procedure

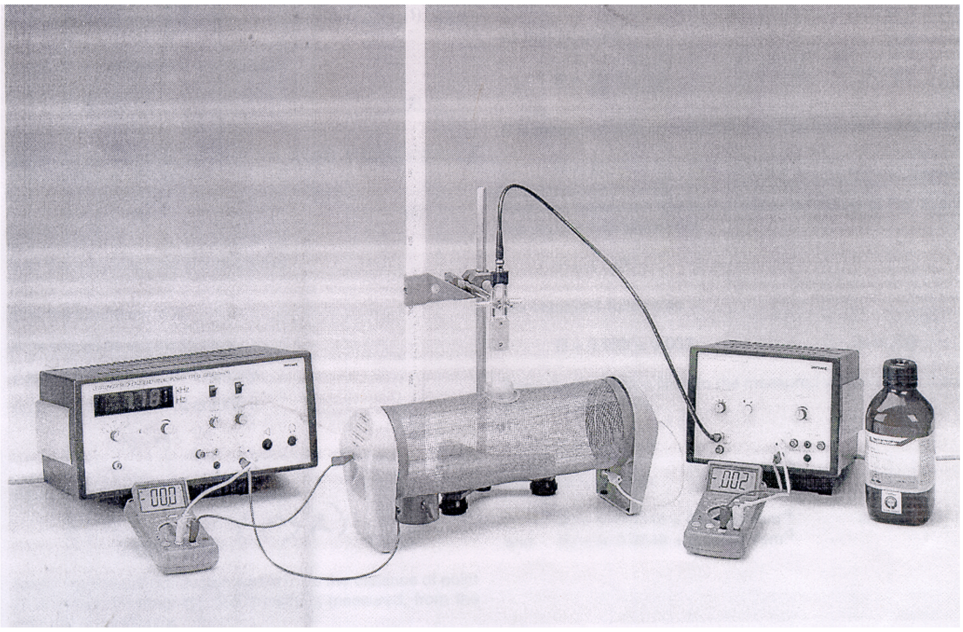

Figure 6.4:

1. Set up the experiment as shown in Figure 7.4.Place the induction coil around 4cm above the axis of hollow cylinder. Change the current amount and measure the induction. Fill the Table 7.1.

2. Keep the current at $1A$. Change the position of induction coil. Fill the Table 7.2.

REPORT SHEET

EXPERIMENT 6: MAGNETIC FIELD INSIDE A CONDUCTOR

Student's Name:
Experiment Date:
Group Member Name(s):
Laboratory Bench Number:
Assistant's Name and Signature:

Data and Calculations

Table 7.1

I (Amper, A)	V (Volt, V)
0.1	
0.2	
0.3	
0.4	
0.5	
0.6	
0.7	
0.8	
0.9	
1.0	

Table 7.2

$r(cm)$ (distance from the axis of the conductor)	V (Volt, V)

Draw the graph of magnetic field inside a conductor as a function of the current flowing.

Draw the graph of magnetic field inside a conductor as a function of the position r.

Discussion

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Chapter 7

ELECTRON SPIN RESONANCE

Purpose

Electron spin resonance in DPPH, determining the magnetic field as a function of the resonance frequency and for three different resonance frequencies and resonance absorption of a passive rf oscillator circuit.

Introduction

Since electrons have charge e and are 'spinning' on their axis, they have a magnetic dipole moment μ. In the presence of an external magnetic field B , a free electron will therefore acquire a potential energy given by:

$$E = -\vec{\mu} \cdot \vec{B} \tag{1}$$

The relationship between magnetic moment μ and the spin angular momentum $\vec{S}$ can be written as:

$$\vec{\mu} = \gamma \vec{S} \tag{2}$$

where γ is the gyromagnetic ratio. You may show that if an electron is a uniform sphere with homogeneous charge distribution, one expects γ to be $e/2m$. Real electrons have a larger magnetic moment than this simple model predicts, and the discrepancy is often written in terms of the *Lande g factor*:

$$g \equiv \frac{\gamma}{e/2m} > 1 \tag{3}$$

If we consider the magnetic field $\vec{B}$ to be pointing in the z direction, the potential energy is:

$$E = \mu_z B_z \tag{4a}$$

$$E = \gamma S_z B_z \tag{4b}$$

Since we know from quantum mechanics that S_z can only have two values:

$$S_z = \pm\frac{\hbar}{2} \tag{5}$$

the potential energy will only have two values:

$$E = \pm(1/2)\gamma\hbar B_z \tag{6}$$

The difference in the two energies is then:

$$\triangle E = \gamma\hbar B_z \tag{7}$$

For single electron ;

- The two spin states have the same energy in the absence of a magnetic field
- The energies of spin states diverge linearly as the magnetic field increases

Therefore;

- Without a magnetic field, there is no energy difference to measure
- The measured energy difference depends linearly on the magnetic field

If a photon incident on an electron has an energy corresponding to this energy difference and the electron is in the lower energy state, the photon may be absorbed, inducing the electron to 'flip' its orientation: this phenomenon is *electron spin resonance*. Since the photon energy is just $h\nu$, we can re-write Equation (7) in terms of the frequency of the incident radiation:

$$\nu = \frac{1}{2\pi}\gamma B_z \tag{8}$$

In ESR technique; sample is placed in a microwave cavity (i.e. high frequency em radiation) in an electromagnet. The trapped electrons in the material either align with or against the magnetic field in which they find themselves. The magnetic field is slowly changed , for a given frequency, there is a certain value of magnetic field at which the electrons resonate i.e. change direction of alignment. In so doing, microwave energy is absorbed and no trapped electrons. Therefore, measure of age i.e. time since signal zeroed. Each type of electron trap has a characteristic g value which is related to microwave frequency and magnetic field strength.

$$g = 0.7144\ \frac{microwave\ frequency}{magnetic\ field\ strength}$$

Resonance occurs when the reactance of an inductor balances the reactance of a capacitor at some given frequency. In such a resonant circuit where it is series resonance, the current will be maximum and offering minimum empedance. In parallel resonant circuits the opposite is true. The rf coil is part of a high quality parallel resonance circuit.In the resonance case the sample absorbs rf energy, thus changing the AC resistance (damping) of the oscillatory circuit. By triggering the two-channel oscilloscope with the modulation signal of the magnetic field it is possible to simultaneously display the curves for field modulation and ESR absorption.The resonance frequencies f at differnet field strengths B are directly indicated on a digital frequency counter, built-in to the ESR Control unit.

So far we have only discussed free electrons. However in chemical free radicals there is one unpaired electron per molecule and these substances are paramagnetic. These unpaired electrons are almost entirely uninfluenced by their orbital motion. Thus it is possible to obtain a good value for the free electron gyromagnetic ratio from measurements on a free radical. This in turn will allow you to calculate the Lande g factor. The free radical you will use in this experiment is diphenylpicryl hydrazyl (DPPH, $(C_6H_5)_2NN(\bullet)C_6H_2(NO_2)_3$); it is contained in the small 'test-tube'. Note that it fits neatly inside each of the 3 small copper coils.

An unpaired electron interacts with its envirenment and the details of ESR spectra depend on the nature of those interactions. Two ways are conceivable for scanning an absorption spectrum;

1. To sweep the microwave at a constant magnetic field

or

2. To sweep the magnetic field at a constant microwave frequency.

Since it is technical much more feasible to realise the second way, the external magnetic field is commonly swept at a constant microwave frequency. Due to amplification technique the absorption signal is recorded as the first derivative. $\triangle E = h\nu = g\mu_B B_z$. g is the proportionality constant approximately equal to 2 for most samples, but varies depending on the electronic configuration of the radical or ion.

The magnetic field B_z will be supplied by the 2 Helmholtz coils. Rather than a fixed B_z, you will use an AC current (60 Hz is very slow compared to atomic times, so the fact that the field is varying doesn't matter) as the field sweeps through the resonance point you will then see the absorption of the high frequency photons. **Never exceed 1 A current through the coils!** Recall that the field is most uniform when the distance between the coils is equal to their radius. Also, the central field generated by a pair of coils is given by:

$$B = (4/5)^{3/2}\frac{\mu_o nI}{R} \quad \text{Tesla}$$

where:

$\mu_o = 4\pi x 10^{-7}\ Wb\ A^{-1}\ m^{-1}$
R = the radius of the coils
n = the number of turns
I = the current

You should monitor the current going into the coils both with an ammeter and by looking at the voltage drop across the supplied 1Ω resistor with a scope.

The heart of the apparatus are the 2 units from Leybold (Figure 8.1). One, called the ESR Basic Unit, contains a socket for mounting one of the small copper coils containing the DPPH sample, a DIN cable, and two small knobs for controlling the strength and frequency of the high-frequency photons. The unit will generate a RF field inside the copper coil. The 3 different copper coils give you 3 different ranges of frequencies. Can you predict which of the copper coils will give the maximum frequency?

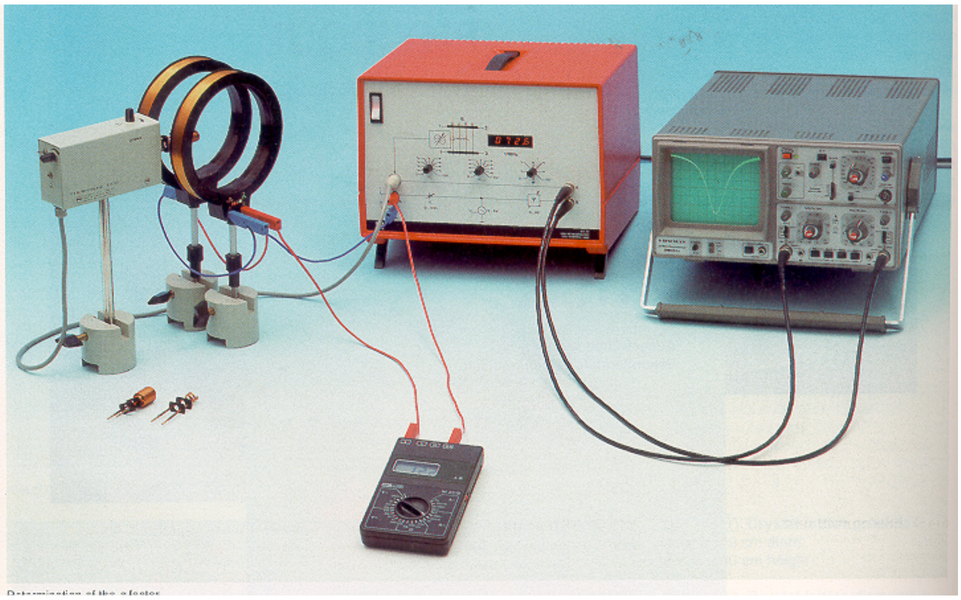

Figure 7.1:

The other is the ESR Control Unit which provides all the required voltages and also digitally indicates the frequency of the oscillatory circuit.

Finally, a couple of experimental tips:

- the axis of the copper coil should be perpendicular to the extern field B_z .

- if you can find a combination of frequency and current so that the two peaks have just merged into one, then the corresponding current at resonance is just the peak current going through the coils.

You may also wish to ponder and/or investigate the following:

- The ESR signal may not be exactly symmetric about the maximum current point. Why?

- Is the relation Equation (8) true over a wide range of frequencies, ie: is the effect truly linear?

- What is the physical interpretation of the width of the peak?

- How does the Basic Unit work? What is the knob that adjusts the frequency connected to? What parameter of the circuit is being fed out of the Y socket?

ESR has a wide range of applications in physics, material science, chemistry, biology and medicine. ESR spectra are characterized by;

- The form of the absorption curve,
- The position of the resonance field,
- The line width,
- The area under the absorption curve

From these parameters;

- The g value
- The relaxation rates $1/T1$ and $1/T2$
- The spin susceptibility χ_s

can be derived.

Examples of Experiments

Verification of electron spin resonance
Magnetic field as a function of resonant frequency (linearity of Zeeman interaction)
Measurement of the gyromagnetic ratio and factor of g
ESR line width
Signal amplitude as a function of resonant frequency

Equipments

ESR Basic Unit with base
ESR Control Unit
3 RF coils and a DPPH sample in a vial
Passive resonant circuit

Current measuring lead
Pair of Helmholtz coils with base
Multimeter
Dual trace oscilloscope
Connecting wires
xyt recorder

Technical Data

ESR Basic Unit

Power supply: 12V, 175mA
Frequency range of each coil:
approx. 13 to 30 MHz
approx. 30 to 75 MHz
approx. 75 to 130 MHz
Voltage at rf coil: approx. 6 V_{pp} (with respect to earth) at 13MHz and maximum amplitude setting
ESR signal: approx. 1 to 6 V (frequency dependent)
Frequency divider: 1000:1
Frequency response for digital counter: TTL
Resonance meter current (DC): approx. $100\mu A$
Frequency range of the passive resonant circuit: 10 to 50 MHz
ESR probe head (variable high frequency transmitter, frequency divider and low frequency signal amplifier)
Plug-in-coils, for different frequency ranges
Measuring cable, for employing the unit as a resonance meter
Passive electric resonant circuit, for investigating the dependence of the resonant frequency on the magnetic field
DPPH probe

ESR Control Unit

Power supply for magnetic field:
0 to 10 V DC,
0 to 5 V AC, continuously adjustible
Current: max 3A (no overload protection)
Adjustible phase difference: 0 to 90^o
Frequency display: 4 decades (MHz)

Connection: 115/230 V, 50/60 Hz, via mains cable

Fuses: for 230 V; T 0.8 B, for 115 V; T 1.6 D

Helmholtz Coils

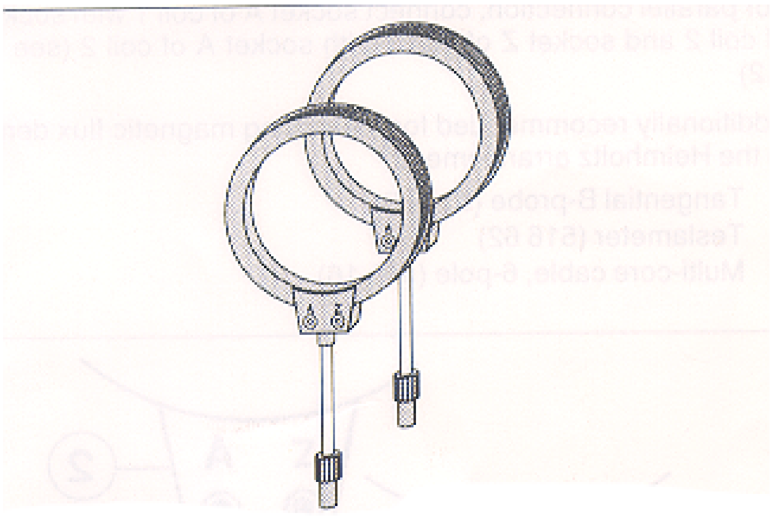

Figure 7.2:

These coils (Figure 8.2) can be used as field and induction coils or as inductive resistor. They can be fitted either -with defined "Helmholtz distance" for generating an approximately homogeneous magnetic field- into the stand for electron tubes or into stand equipment.

Number of turns: 320 per coil

DC resistance: approx. 6.5Ω per coil

Maximum load: 1.5A (continuous), 2A (for short period)

Coil diameter. 13.5 cm

Mean coil distance for Helmholtz arrangement: 6.8 cm

Field strength $H = 34x10^2 m^{-1} I$ (I coil current, in Helmholtz arrangement)

Connections: Two 4mm sockets, with identification of beginning (A) and end (Z) of winding

Do not exceed the maximum permissible current and observe it.

Connect the pair of coils so that they have the same winding sense. If the coil connections are at the outside, proceed as follows:

For series connection, connect socket Z of coil 1 with socket Z of coil 2.

For parallel connection, connect socket A of coil 1 with socket Z of coil 2 and socket Z of coil 1 with socket A of coil 2.

Procedure

1. Set the Helmholtz coils at the proper spacing of 1/2 diameter. Connect the ESR Basic Unit with the middle-sized rf coil, as well as the Helmholtz coils to the ESR Control unit, and turn on both power switches (Figure 8.3). Watch the dedector output on the scope. Adjust the tuning knob on top of the ESR Basic Unit to get a frequency reading near the high end (say 60-70 MHz). Be sure the DPPH sample is in the coil.

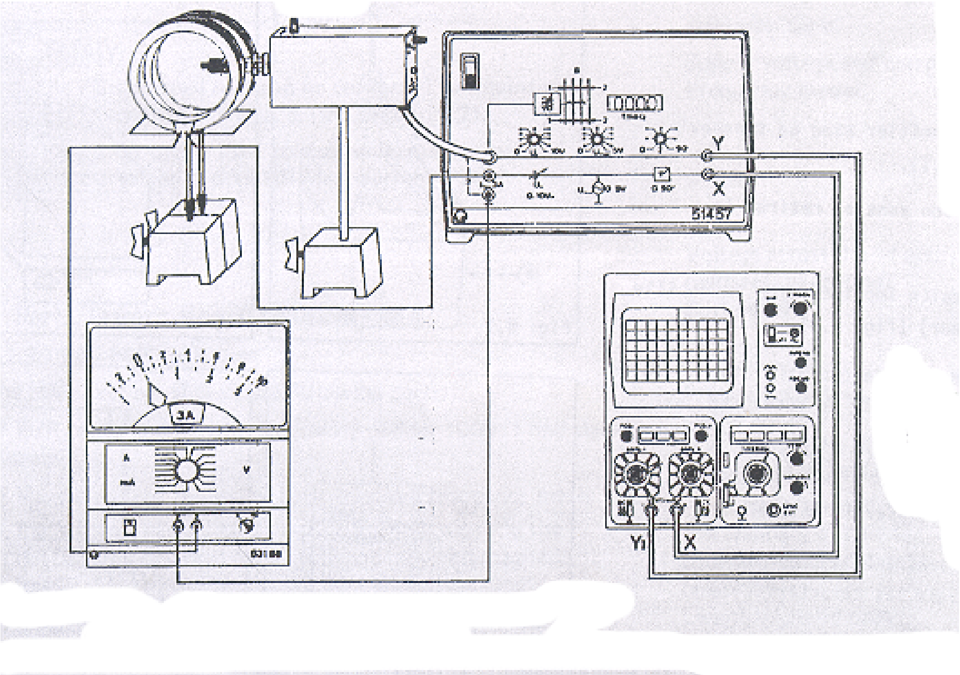

Figure 7.3:

2. Three knobs on the ESR Control Unit control the dc and ac current to the Helmholtz coils, and the phase shift of the signal sent to the scope (for convenience and viewing). Set a moderate ac level and adjust the dc current until you see indication of a resonance (somewhere near mid-range). This should show up as a dip in the somewhat noisy Y output from the detector each time the modulation takes the total field through resonance, the dip indicating a decrease in the level of oscillation due to absorption of power in the DPPH. Adjust the amplitude knob on the back of the ESR Basic Unit for the best signal to noise ratio.

3. Determine the magnetic field at resonance. This is the field due to the dc current, provided you adjust things so that the dip occurs at the zero crossing of the modulation. There are two good ways to do this: Adjust for symmetric dips in a time trace (MTB), or for a symmetric dip pattern with the scope in XY mode (X-DEFL). For the latter, reduce the modulation level until you see only half the dip; the phase shift may also be useful here. Check that the coil spacing is correct for the Helmholtz formula to be appropriate. Do this for a number of frequencies over as wide a range as possible.

4. Determine the with of the resonance (in magnetic field units). Is it frequency dependent? A limitation of these relatively low-field measurements is that the intrinsic width must be quite small; at least smaller than the field used.

REPORT SHEET

EXPERIMENT 7: ELECTRON SPIN RESONANCE

Student’s Name:
Experiment Date:
Group Member Name(s):
Laboratory Bench Number:
Assistant’s Name and Signature:

Questions

1. What is the magnetic moment of free electrons?

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2. What is the Lande g factor? Why is it needed?

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3. How does g depend on the envirenment of the electron?

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4. If the magnetic moment of the electron is aligned along the z-axis with no external magnetic field, describe the effect of turning on an external field aligned along the x-axis.

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5. What is Larmor frequency and γ, the gyromagnetic ratio?

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6. Show that for a free electron in a 5 kG magnetic field the Larmor frequency is 14 GHz.

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7. Why are microwaves necessary to study the electron spin resonance?

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8. How do microwaves differ from light?

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9. What is the quantum mechanical coupling probed by ESR?

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10. What selection rules are important in determining the experimental frequency and/or the magnetic field? and why?

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11. Do you expect the resonance frequency to change if the sample is changed?

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Discussion

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Chapter 8

ELECTRICAL CONDUCTION IN SOLID BODIES

Purpose

Measuring the temperature dependency of a noble metal resistor and a semiconductor resistor.

Introduction

Energy Band Theory of Solids

The differences in behavior of a conductor, semiconductor and insulator can be explained by the electron energy band theory of solids. The idealized energy band configuration for the outermost electrons in each type of solid is shown in Figure 11.1.

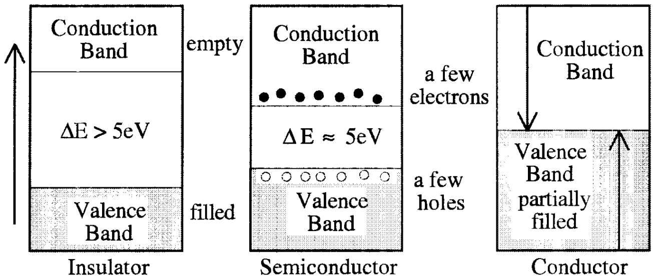

Figure 8.1:

Only electrons in the conduction band and holes in the valence band will contribute to the conduction of current. No electron can have an energy in the "forbidden" energy gap. In an insulator, the energy gap is large and essentially no electrons have sufficient energy to reach the conduction band. At absolute zero, all the electrons would reside in the valence band and would be tightly bound to the individual atoms.

In a good conductor, there is no energy gap and the conduction and valence bands may overlap. Hence electrons can readily be available for conduction of current - even at considerably low temperatures.

If the temperature of a solid is raised, the resistance is likely to change because of two opposing tendencies:

(a) An increase in temperature is an increase in the vibration amplitudes of the atoms in the crystal lattice. This causes an increased frequency of collisions between the charge carriers and the lattice, thus reducing the average drift velocity of the carriers. For a constant applied potential difference, the reduced motion of the carriers implies a reduced current, and hence resistance is increased.

(b) The increased amplitudes of vibration may break some bonds between the valence electrons and the lattice atoms, hence releasing more charge carriers and reducing the resistance.

Electrical Conduction in Metals

Electron Mobility

Electrons are accelerated in an electric field E, in the opposite direction to the field because of their negative charge. The force acting on the electron is $-eE$, where e is the electric charge. This force produces a constant acceleration so that, in the absence of obstacles (in vacuum, like inside a TV tube) the electron speeds up continuously in an electric field. In a solid, the situation is different. The electrons scatter by collisions with atoms and vacancies that change drastically their direction of motion. Thus electrons move randomly but with a net drift in the direction opposite to the electric field. The drift velocity is constant, equal to the electric field times a constant called the *mobility* μ,

$$v_d = -\mu_e E$$

which means that there is a friction force proportional to velocity. This friction translates into energy that goes into the lattice as heat. This is the way that electric heaters work. The electrical conductivity is:

$$\sigma = n|e|\mu_e$$

where n is the concentration of electrons (n is used to indicate that the carriers of electricity are negative particles).

Electrical Resistivity of Metals

The resistivity then depends on collisions. Quantum mechanics tells us that electrons behave like waves. One of the effects of this is that electrons do not scatter from a perfect lattice. They scatter by defects, which can be:

atoms displaced by lattice vibrations
vacancies and interstitials
dislocations, grain boundaries
impurities

One can express the total resistivity R_{tot} by the Matthiessen rule, as a sum of resistivities due to thermal vibrations, impurities and dislocations.

In a metal, the number of "conduction" or free electrons is approximately independent of temperature (except for very low or very high temperatures). Tendency (a) is completely dominant and the resistance of all metals increases with temperature. If the temperature variation is not too large, the resistance as a function of temperature is approximately given by the equation

$$R = R_o[1 + \alpha(T - T_o)] \qquad (1)$$

where R_o is the resistance of the metal at a reference temperature (usually 0^oC), and R is the resistance at any other temperature $T(^oC)$. The quantity α is the temperature coefficient of resistance measured at tempreature T_o and is a constant characteristic of the metal.

Electrical Conduction in Semiconductors

There are materials in which resistance decreases with increasing temperature. A thermistor is an example of such a material. Thermistors are very sensitive to even small changes of temperature, therefore they are often used as thermometers. It is made of semiconductors, such as oxides of manganese, nickel and cobalt mixed in the desired proportion with a binder and pressed into shape.

Semiconductors can be intrinsic or extrinsic. Intrinsic means that electrical conductivity does not depend on impurities, thus intrinsic means pure. In extrinsic semiconductors the conductivity depends on the concentration of impurities.

Conduction is by electrons and holes. In an electric field, electrons and holes move in opposite direction because they have opposite charges. The conductivity of an intrinsic semiconductor is:

$$\sigma = n|e|\mu_e + p|e|\mu_h$$

where p is the hole concentration and μ_h the hole mobility. One finds that electrons move much faster than holes:

$$\mu_e > \mu_h$$

In an intrinsic semiconductor, a hole is produced by the promotion of each electron to the conduction band. Thus:

$n = p$

Thus, $\sigma = 2n|e|(\mu_e + \mu_h)$ (only for intrinsic semiconductors)

The thermal vibration of the atoms can impart energy ($\sim kT$) to the electrons such that some of them break free from their covalent bonds and can migrate through the crystal as part of the conduction current. From Fermi-Dirac statistics, the number ne of electrons per m^3 which are thermally excited to the conduction band at a temperature $T(K)$ is given by the expression

$$n = N_c e^{-E_g/2kT} = 4.83x10^{21} T^{3/2} e^{-E_g/2kT} \qquad (2)$$

where E_g is the energy gap between the valence and conduction band, k is Boltzmann's constant (1.38 x $10^{-23} J/K$) and N_c is the effective density of states in the conduction band. Equation (2) is only valid for a pure (intrinsic) semiconductor where the number of conduction electrons equals the number of positive holes in the valence band. As the temperature increases, the number of electrons (and holes) increases so the resistance of the semiconductor decreases and tendency (b) is said to dominate. Since the exponential term $e^{-E_g/2kT}$ far outweighs any other factors, it follows that the resistance R at a temperature $T(K)$ can be approximately given by the equation

$$R = R_o e^{(1/T - 1/T_o)E_g/2k} \qquad (3)$$

where R_o is the resistance of the semiconductor at a reference temperature T_o (usually 273K).

Extrinsic semiconductors have, in addition to this dependence, one due to the thermal promotion of electrons from donor levels or holes from acceptor levels. The dependence on temperature is also exponential but it eventually saturates at high temperatures where all the donors are emptied or all the acceptors are filled.

This means that at low temperatures, extrinsic semiconductors have larger conductivity than intrinsic semiconductors. At high temperatures, both the impurity levels and valence electrons are ionized, but since the impurities are very low in number and they are exhausted, eventually the behavior is dominated by the intrinsic type of conductivity.

Technical Data

Noble Metal and Semiconductor Resistors

These resistors are used for quantitative investigation of the temperature dependency of the ohmic resistance of two solid bodies with different types of conductivity. Hence, they enable experiments to be carried out on the conductivity in solid bodies.

Noble metal resistor: It is a platinum wire, sealed in a glass tube.

Semiconductor resistor: It is a NTC (Negative Temperature Coefficient) resistor, sealed in a glass tube.

4mm sockets, connected with resistors.

Borehole, diameter 8mm, for positioning of a thermometer, as required for the measurements, in the immediative vicinity of resistors while they are heated in the electric oven.

	Noble metal resistor	Semiconductor resistor
Temperature range	-100^{o}C – +400^{o}C	-100^{o}C – +200^{o}C
Resistance range	approx.60Ω – 240Ω	approx.20kΩ – 5Ω
Resistance at 20^{o}C	approx.100Ω	approx.200Ω

Dewar Vessel

The dewar vessels (Figure 11.2) featuring low thermal absorption and very good insulation against heat losses are used in calorimetric measurements for immersion of solid test specimens into liquids.

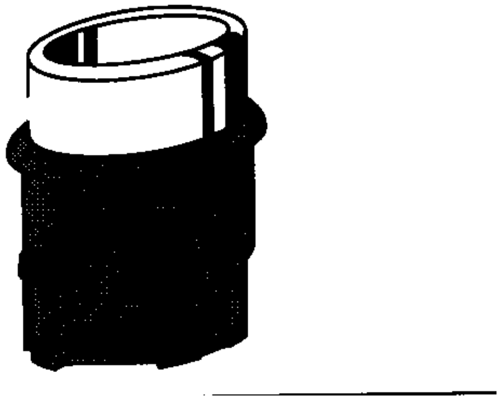

Figure 8.2:

It consists of plastic base and dewar vessel, 250 ml, double-walled glass jacket, highly evacuated, silver-coated, internal diameter 7 cm, depth 9 cm.

Do not let hard objects fall into the Dewar vessel. Protect its walls against scratches by sharp objects. Risk of breakage. Risk of implosion.

Demonstration Bridge

The apparatus (Figure 11.3) is used together with standard resistors and a ammeter as a zero indicator to determine unknown resistances in a Wheatstone bridge circuit. It is also suitable for investigating voltage drop along a resistance wire.

Resistance wire; constantan

Length: 1 m
Resistance; approx. 4Ω
Maximum allowable voltage; 2 V
Maximum allowable current; 0.5 A
4 mm sockets for the power supply and the resistors
Sliding contact with 4 mm sockets
Baseplate with scale;
Length: 1 m
Scale: 10 cm divisions with cm and mm graduations

Determining the Resistance by means of a Wheatstone Bridge Circuit

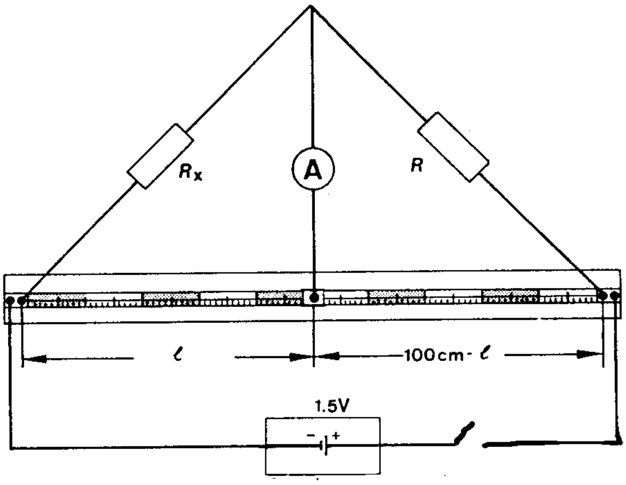

Figure 8.3:

Choose a standard resistor which is approximately equal to, or at least of the same order of magnitude as the unkown resistance R_x (smallest measurement inaccuracy for l when the sliding contact is centrally positioned).

For determining a resistance value; balance the bridge with the sliding contact so that the ammeter shows no deflection.

$$R_x = \frac{l}{100cm - l} R$$

Equipments

Noble metal resistor
Semiconductor resistor
Demonstration bridge
Electric oven
Morse key
Measuring junction box
Ammeter, zero point in centre
Standard resistors
Thermometer
Dewar vessel with cooling agent (liquid nitrogen)
Single cell battery, 1.5V
STE battery holder
Plugboard

Procedure

Set the equipments as shown in Figure 11.4.

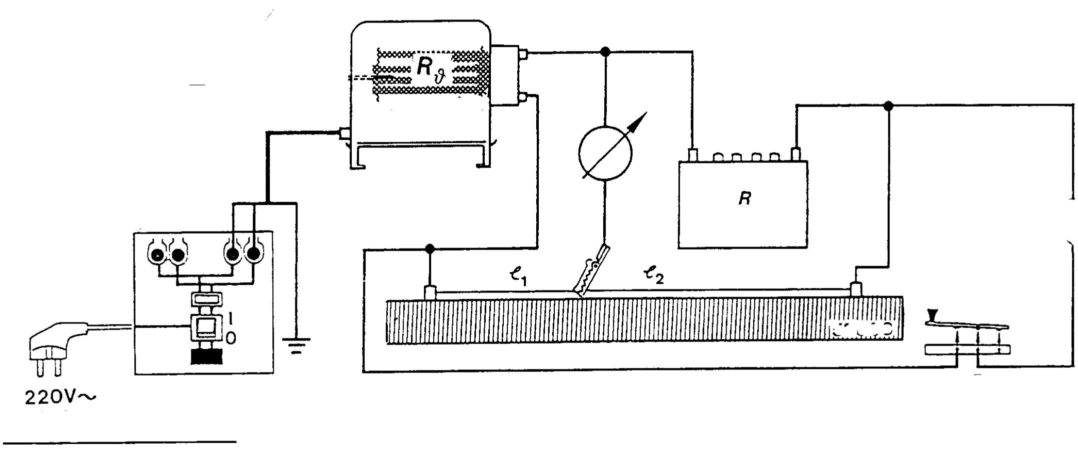

Figure 8.4:

It is advisable to study the resistance as a function of temperature in the following sequence:

1. at room temperature
2. during heating in an electric oven
3. during cool-down in a freezing bath

Heating in the Electric Oven

1. Introduce the thermometer into the borehole at the rear of the oven until the thermometer is in the immediative vicinity of resistors (noble metal or semiconductor).

2. Before reading off any pair of temperature/resistance values, wait until temperature has balanced with the oven voltage switched off, every time measuring the reversal point of temperature.

3. When the thermometer indicates the maximum permissible value (200^oC for semiconductor resistor, 400^oC for noble metal resistor), immediately remove the resistor from the oven.

Cool-down in the Freezing Bath

1. Before immersing the heated resistor into the freezing bath, precool it by means of a fan.

2. Cool down the resistor to approximately -50^oC to -100^oC directly above the surface of liquid nitrogen.

3. Measure the resistor while it is slowly heated to room temperature.

4. Arrange the thermometer in close vicinity to the resistor (it is advisable to use heat conducting paste to improve contact).

REPORT SHEET

EXPERIMENT 8: ELECTRICAL CONDUCTION IN SOLID BODIES

Student's Name:
Experiment Date:
Group Member Name(s):
Laboratory Bench Number:
Assistant's Name and Signature:

Data and Calculations

Table 11.1

Conductor 1

T(^oC)	$l_1(cm)$	$l_2(cm)$	$R_o(\Omega)$	$R_x(\Omega)$

Table 11.2

Conductor 2

T(^oC)	$l_1(cm)$	$l_2(cm)$	$R_o(\Omega)$	$R_x(\Omega)$

1. Which device behaves as a metal? As a semiconductor? Discuss.

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2. For the metal, plot a graph to test the validity of Equation (1) and obtain an experimental value for α. Is there any evidence that changes with temperature? Graphically determine a value for R_o. At what temperature would the resistance R becomes zero according to Equation (1). What does this suggests about the validity of Equation (1) for all temperature ranges?

3. For the semiconductor, plot a graph of lnR versus $1/T$ to test Equation (3). Graphically determine the value of the energy gap E_g. What would the resistance of the semiconductor be at absolute zero? Why?

Is your value for E_g reasonable, given that for many semiconductors near room temperature.

Questions

1. Draw energy band structures for insulators, conductors and semi-conductors and describe their characteristics.

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2. Describe the difference between Bose-Einstein statistics and Fermi-Dirac statistics. Which are play in this lab? Describe how they vary as a function of temperature (Note: a picture is worth a thousand words!)

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Discussion

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Chapter 9

PHOTOCONDUCTIVITY

Purpose

Recording the current-voltage curve of a CdS photoresistor at different illuminance values and constant wavelength. The behavior of the current flowing through the CdS photoresistor will be investigated when a voltage is applied. During each measuring series, the luminous intensity acting on the photoresistor from a light source will remain constant. Each measurement series will then be used to produce a current-voltage curve for the respective irradiance.

Introduction

Photosensitive devices can be divided into photovoltaic devices and photo emissive devices. CdS cells are a type photoconductive device. They are semiconductor sensors that utilize the photoconductive effect in which light entering the photoconductive surface reduces the resistance. A voltage is applied to both ends of a CdS cell and the change in resistance due to light is output as a current change signal. Despite of small size, the output current per photoconductive surface area is large enough to drive relays directly. For this reason, CdS cells are used in a variety of fields.

Photoconductive Effect

Figure 12.1 is a schematic diagram of a CdS cell and its operation circuit. An electrode is set at each end of the photoconductor. In darkness, the photoconductor resistance is very high and when a voltage is applied, the ammeter shows only only a small dark current. This is the CdS photoconductor's characteristic thermal equilibrium current. When light is incident on this photoconductor, a current (I) flows. Figure 12.2 shows the current that flows when the amount of light is increased.

Here are the basic principles of the photoconductive effect.

I) Directly beneath the conduction band of the CdS crystal is a donor level and there is an acceptor level above the valence band. In darkness, the electrons and holes in each level are almost crammed in place in the crystal and the photoconductor is at high resistance.

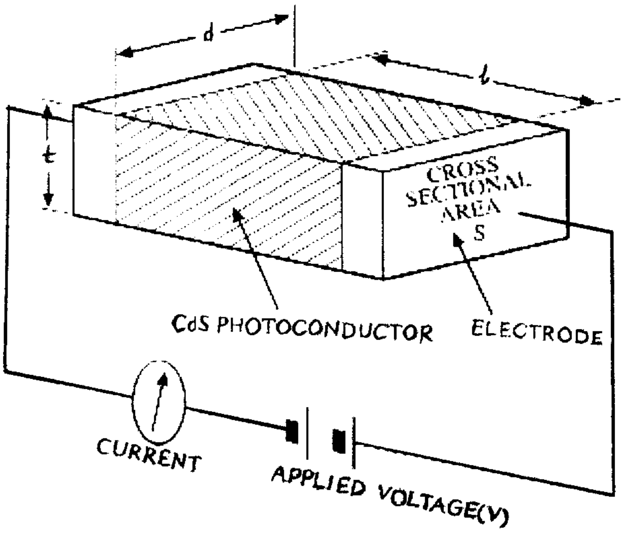

Figure 9.1:

II) When light illuminates the CdS crystal and is absorbed by the crystal, the electrons in the valence band are excited into the conduction band. This creates pairs of free holes in the valence band and free electrons in the conduction band, increasing the conductance.

III) Furthermore, near the valence band is a separate acceptor level that can capture free electrons only with difficulty, but captures free holes easily. This lowers the recombination probability of the electrons and holes, and increases the number for electrons in the conduction band for N-type conductance.

The increase in conductance in (II) requires that the light energy be greater than the band gap E_g. For CdS with a band gap of 2.41eV, the absorption edge wavelength λ is

$$\lambda = \frac{hc}{E_g} \simeq 515\text{nm}$$

Therefore, the CdS crystal absorbs light with a wavelength shorter than 515nm and lets light with a wavelength longer than 515nm betransmitted. Therefore, the photoconductor's absorption edge wavelength determines the spectral response characteristic on the long wavelength side. The sensitivity of CdS drops at wavelength shorter than 515nm. This is because at short wavelengths, the light is absorbed near the surface of the crystal, increasing the local charge density and inducing electron hole recombination, and also because there are lattice defects at the crystal surface, they promote the recombination.

Until the carries generated in (II) and (III) recombine, electrons are injected from one electrode and pulled out by the other. When these carriers last longer and they move more, the conductance increases greatly. The conductance $\triangle\sigma$ is given by the following equation.

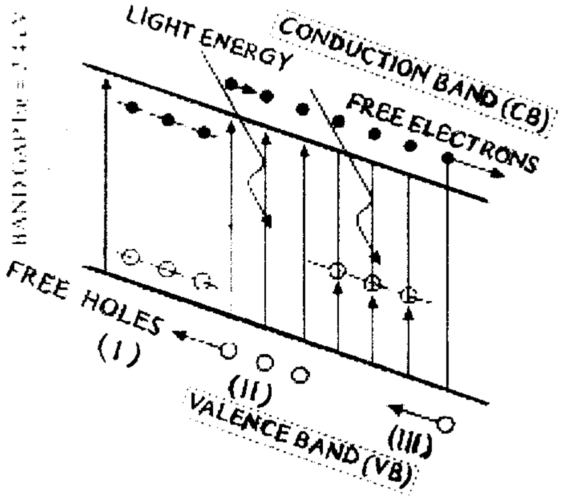

Figure 9.2:

$\triangle\sigma = en(\mu_e\tau_e + \mu_p\tau_p)$

where μ_e, μ_p; free electron and free hole movement (cm^2/Vs)
τ_e, τ_p; free electron and free hole life (s)
n; number of generated carriers per second per cubic volume

For a CdS cell, $\mu_e\tau_e \gg \mu_p\tau_p$ and conductance by free holes can be ignored. Then it becomes an N-type semiconductor. Thus,

$\triangle\sigma = en\mu_e\tau_e$

Here, the gain G is defined as how many electrons flow between the electrodes due to excitation by one photon in the CdS photoconductor (until the carrier lifespan is over).

$G = \tau_e/t_t$

where t_t $(transit\ time\ between\ electrodes) = \dfrac{l^2}{V\mu_e}$
l; distance between electrodes
V; voltage applied

Therefore,

$G = \dfrac{\mu_e\tau_e V}{l^2}$

If, for example, $\mu_e = 300cm^2/Vs$, $\tau_e = 10^{-3}s$, $l = 0.2mm$ and $V = 1.2V$, then the gain is 900. This means that there is multiplication in the CdS photoconductor and that the CdS is highly sensitive.

The sensitivity of CdS is the change in resistance, i.e. the change in current in response to change in light. As Figure 12.1 shows, if the distance between the electrodes is l, the cross-sectional area of the photoconductor is S and the voltage applied is V, then from Ohm's law;

$$\triangle I \propto \frac{\triangle\sigma SV}{l} = \frac{\triangle\sigma tdV}{l}$$

If the conductance $\triangle\sigma$ and the photoconductor thickness t are held constant, then,

$$\triangle I \propto \frac{d}{l} \rightarrow \triangle R \propto \frac{l}{d}$$

This l/d is an important factor in designing the electrode configuration. In other words, the shorter distance between the electrodes and the greater the electrode length, the higher the sensitivity and the lower the cell resistance. Thus, the electrode patterns for high-sensitivity CdS cell consist of many zig-zags.

Equipments

Power supply unit for tube experiments
Lamp housing and a lamp 6V/30W
Aspherical condenserwith diaphragm slider
Adjustable slits
Projection objective
Flint glass prism and prism table
Pair of polarizing filters
Lens, f=100mm
Photoresistor LDR
Small optical bench with short holder
Small optical bench with long holder
Swivel joint with protractor scale
Stand bases, stand rods and multiclamps
Multimeter
Connecting leads

Procedure

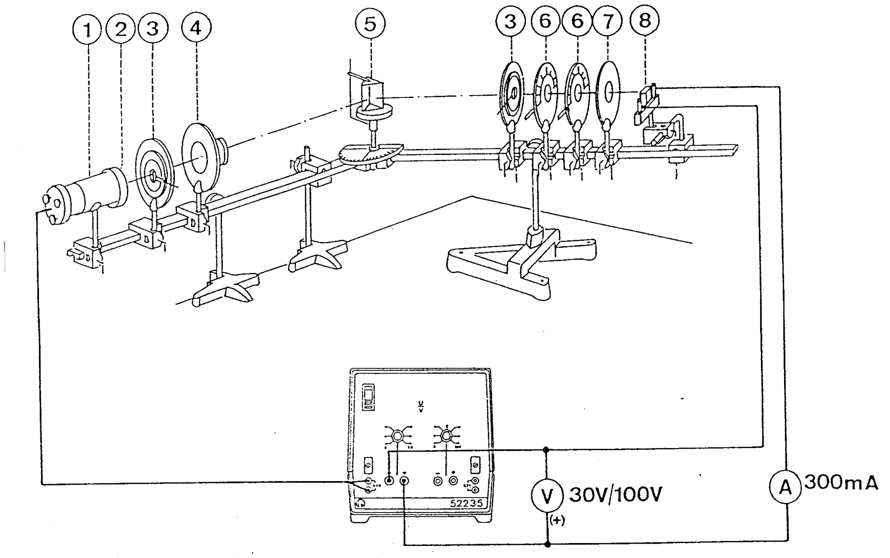

Figure 9.3:

(1) Light source
(2) Condenser
(3) Entrance or emergence slits
(4) Projection objective
(5) Flint glass prism
(6) Polarizer or analyzer
(7) Conversion lens f= 100mm
(8) Photoresistor LDR

1. Measurements should be carried out with the room darkened to suppress the influence of room light on the photocurrent (not a total black-out so that it is still possible to read off the instrument display). It is also recommended to place a black cover on the photoresistor which is only open towards the ray path. In this way, the "dark photocurrent" can easily be kept negligibly small.

2. Set the entrance and emergence slits arbitrarily, but remember that the smaller the gap width, the sharper the color separation. It is advantageous to select the gap width of the entrance slit so that it is at least as large as the emergence slit.

3. With slit widths of 0.3mm and less, the colors yellow, green, blue and violet, amongst others, can be separated at least as exactly as when using the filter set for these colors.

4. Before reading off each measurement value, it is recommended to allow a certain waiting period, approximately 20s, until the photocurrent has reached a stationary value.

5. Using lens (2), fully illuminate entrance slit (3). Form a sharp image of the entrance slit on the emergence slit using the projection objective (without prism).

Finally, place the prism in the ray path, adjusting for minimum deflection. Using the lens (7), focus the desired color on the receiver through the emergence slit by moving the mobile path of the optical setup.

6. Set the polarizer to the angle 0^o and the analyzer to the desired angle (α). The radiance J determined in this way is given by; $J = J_o \cos^2 \alpha$

7. The photocurrent (I_{ph}) is now measured step-by-step as a function of voltage (V) with fixed wavelength (λ) and irradiation(J),

$I_{ph} = I_{tot} - Io$

since I_o (dark current) is significantly low in respect of I_{tot},

$I_{ph} \cong I_{tot}$

8. Repeat the experiment for different irradiances, i.e. different angles for α, keeping the same wavelength range.

REPORT SHEET

EXPERIMENT 9: PHOTOCONDUCTIVITY

Student's Name:
Experiment Date:
Group Member Name(s):
Laboratory Bench Number:
Assistant's Name and Signature:

Data and Calculations

Table 12.1

V, V	$I_o(A)$, $\alpha = 0^o$	$I_{tot}(A)$, $\alpha = 0^o$	$I_{tot}(A)$, $\alpha = 30^o$	$I_{tot}(A)$, $\alpha = 60^o$	$I_{tot}(A)$, $\alpha = 75^o$
0					
2					
4					
6					
8					
10					
15					
20					
25					
30					
40					

Discussion

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Chapter 10

I-V CHARACTERISTICS OF SOLID STATE DEVICES

Purpose

The purpose of this lab is to become familiar with the modern laboratory equipment for the experimental physics and to measure the I-V characteristics of a test diode and resistance using the LabView program.

Introduction

Current (I)-voltage (V) curve measurement, i.e. the I-V curve is a simple characterization method for any type of junctions. The I-V curves of solid state devices reflect purely the electronic properties of the junctions. The procedural sections will use the LabView program to measure the I-V characteristics of test diode and resistance.

LabVIEW program

LabVIEW (short for Laboratory Virtual Instrumentation Engineering Workbench) is a platform and development environment for a visual programming language from National Instruments. LabVIEW is commonly used for data acquisition, instrument control, and industrial automation. The programming language used in LabVIEW, also referred to as G, is a dataflow programming language. Execution is determined by the structure of a graphical block diagram (the LV-source code) on which the programmer connects different function-nodes by drawing wires. These wires propagate variables and any node can execute as soon as all its input data become available.

LabVIEW programs are called virtual instruments, or VIs, because their appearance and operation imitate physical instruments, such as oscilloscopes and multimeters. Every VI uses functions that manipulate input from the user interface or other sources and display that information or move it to other files or other computers.

A VI contains the following three components:

I) Front panel: Serves as the user interface.

II) Block diagram: Contains the graphical source code that defines the functionality of the VI.

III) Icon and connector pane: Identifies the VI so that you can use the VI in another VI. A VI within another VI is called a subVI. A subVI corresponds to a subroutine in text-based programming languages.

Front Panel

The front panel is the user interface of the VI. You build the front panel with controls and indicators, which are the interactive input and output terminals of the VI, respectively. Controls are knobs, push buttons, dials, and other input devices. Indicators are graphs, LEDs, and other displays. Controls simulate instrument input devices and supply data to the block diagram of the VI. Indicators simulate instrument output devices and display data the block diagram acquires or generates.

Block Diagram

After you build the front panel, you add code using graphical representations of functions to control the front panel objects. The block diagram contains this graphical source code. Front panel objects appear as terminals on the block diagram.

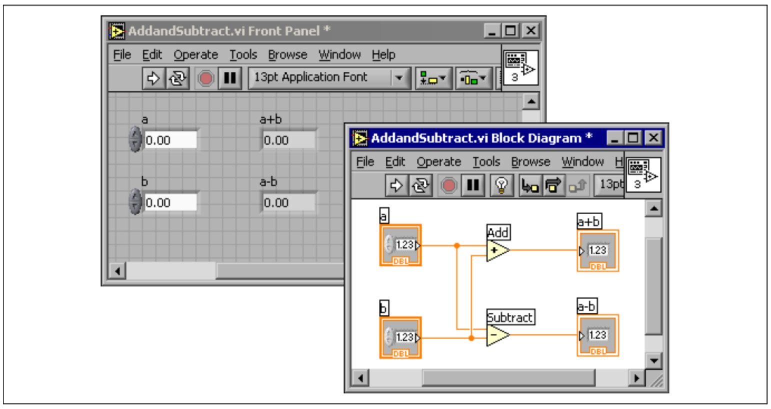

Figure 10.1: Example of a Block Diagram and Corresponding Front Panel

Terminals: The terminals represent the data type of the control or indicator. You can configure front panel controls or indicators to appear as icon or data type terminals on the block diagram.

Nodes: Nodes are objects on the block diagram that have inputs and/or outputs and perform operations when a VI runs. They are analogous to statements, operators, functions, and subroutines in text-based programming languages.

Wires: You transfer data among block diagram objects through wires.

Structures: Structures are graphical representations of the loops and case statements of text-based programming languages. Use structures on the block diagram to repeat blocks of code and to execute code conditionally or in a specific order.

Icon and Connector Pane: After you build a VI front panel and block diagram, build the icon and the connector pane so you can use the VI as a subVI. Every VI displays an icon in the upper right corner of the front panel and block diagram windows. An icon is a graphical representation of a VI. It can contain text, images, or a combination of both. If you use a VI as a subVI, the icon identifies the subVI on the block diagram of the VI.

Review of Scientific Principles

Requirements: To make a current flow through a material, three requirements must be met. 1) An electric field must exist; 2) charge carriers must be present in the material; and 3) the charge carriers must be mobile. To establish an electric field, a voltage is applied to the circuit. The charge carriers are the valence electrons in a conductor, or the electrons in the conduction band and the holes in the valence band of a semiconductor or insulator. The mobility is dependent on the crystal structure and the temperature.

Conductor: For a conductor, such as a metal, the valence electrons occupy partially filled energy levels to form a valence band. The crystal structure of a metal allows the valence electrons in the valence band to move freely through the crystal. However, as the temperature increases, the atoms vibrate with greater amplitude, and move far enough from their equilibrium positions to interfere with the travel of the electrons. Only near absolute zero is the mobility at its maximum value.

Semiconductor: For a semiconductor or insulator, the valence electrons occupy a filled valence band. Electrons must move from the valence band to the conduction band (leaving holes, vacancies, in the valence band). Both the electrons in the conduction band and the holes in the valence band are considered charge carriers. The number of these charge carriers is dependent on the temperature and the material. As the temperature increases, more electrons have the energy needed to "jump" to the conduction band. (Important: The electrons do not move from a place in the crystal, called the valence band, to another place, called the conduction band. The electrons have the energy associated with the valence band, and acquire enough energy to have the energy associated with the conduction band. An energy change occurs, not a position change.)

Doping: Doping of a semiconductor material, by adding atoms with one more or one less valence electron than the base material, is one method of increasing the number of charge carriers (such as adding Ga, with three valence electrons, or As, with five valence electrons, to Ge or Si which has four valence electrons). Addition of a Group V element, such as As, forms an n-type material, which provides new "donor" energy levels. Addition of a Group III element, such as Ga, forms a p-type material, which provides new "acceptor" energy levels. The energy needed for an electron to move from the valence band to the acceptor level as with Ga (forming a hole), or from the donor level to the conduction band as with As (yielding a conducting electron) is less than the energy needed to make the original "jump" from the valence band to the conduction band of the pure semiconductor material. Thus, for a doped semiconductor material as compared to a pure semiconductor material (at the same temperature), the doped semiconductor would have more electrons in the conduction band (n-type), or more holes in the valence band (p-type). For and n-type material, the carrier of electricity is a negative electron. For a p-type material, the carrier is a positive hole. As the temperature increases, the atoms do vibrate with greater amplitude. However, the increase in number of charge carriers has a greater effect on increasing the material's conductivity than the reduction caused by the vibrating atoms.

Resistor: When a voltage is applied across a resistor, an electric field is established. This electric field "pushes" the charge carriers through the resistor. This "push" gives the charge carriers a "drift velocity" in the direction from high potential energy to low potential energy. As the voltage increases, the drift velocity increases. Since the amount of current flowing through a resistor is directly proportional to the drift velocity, the current is directly proportional to the voltage, which produces the electric field, which produces the drift velocity. This is the origin of Ohm's Law.

Diode: However, in a diode, the number of charge carriers is dependent on the number of electrons that have enough energy to move up an energy hill and across the p-n junction, producing current flow through the diode. The size of this hill, or energy barrier, is dependent on the amount and type of dopants in the semiconductor material of which the diode is made. As a voltage is applied (in the forward bias), the size of the hill is decreased, so more electrons have the energy needed to cross the p-n junction producing current flow. The number of electrons with the energy needed to move up the hill and across the junction increases exponentially as the voltage increases. Thus, the current increases exponentially as the voltage increases.

Experiment 1: Resistor I-V Characteristic

The simplest IV characteristic involves a resistor, which according to Ohm's Law exhibits a linear relationship between the applied voltage and the resulting electric current. From Ohm's law we know that the current through a resistor is proportional to its resistance, V=IR. This is an equation of a straight line with a slope of 1/R and a Y-intercept of zero. However, even in this case environmental factors such as temperature or material characteristics of the resistor can produce a non-linear curve.

Experiment 2: Diode I-V Characteristic

Before we can use the PN-junction as a practical device or as a rectifying device we need to firstly ”Bias” the junction, ie connect a voltage potential across it. On the voltage axis above ”Reverse Bias” refers to an external voltage potential which increases the potential barrier. An external voltage which decreases the potential barrier is said to act in the ”Forward Bias” direction. There are 3 possible ”biasing” conditions for the standard Junction Diode and these are:

I) Zero Bias - No external voltage potential is applied to the PN-junction.

II) Reverse Bias - The voltage potential is connected negative, (-ve) to the P-type material and positive, (+ve) to the N-type material across the diode which has the effect of Increasing the PN-junction width.

III) Forward Bias - The voltage potential is connected positive, (+ve) to the P-type material and negative, (-ve) to the N-type material across the diode which has the effect of Decreasing the PN-junction width.

Zero Bias:

When a diode is connected in a Zero Bias condition, no external potential energy is applied to the PN-junction. However if the diodes terminals are shorted together, a few holes (majority carriers) in the P-type material with enough energy to overcome the potential barrier will move across the junction against this barrier potential. This is known as the ”Forward Current” and is referenced as I_F. Likewise, holes generated in the N-type material (minority carriers), find this situation favourable and move across the junction in the opposite direction. This is known as the ”Reverse Current” and is referenced as I_R, as shown below.

Zero Biased Diode:

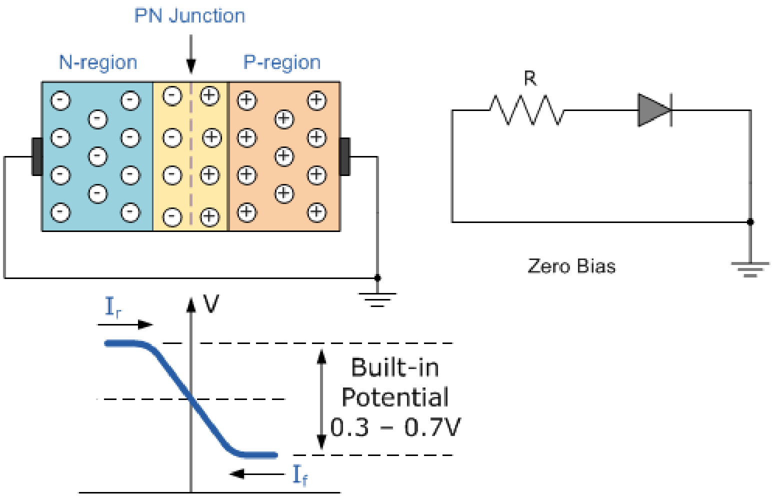

Figure 10.2:

An "Equilibrium" or balance will be established when the two currents are equal and both moving in opposite directions, so that the net result is zero current flowing in the circuit. When this occurs the junction is said to be in a state of "Dynamic Equilibrium". This state of equilibrium can be broken by raising the temperature of the PN-junction causing an increase in the generation of minority carriers, thereby resulting in an increase in leakage current.

Reverse Bias:

When a diode is connected in a Reverse Bias condition, a positive voltage is applied to the N-type material and a negative voltage is applied to the P-type material. The positive voltage applied to the N-type material attracts electrons towards the positive electrode and away from the junction, while the holes in the P-type end are also attracted away from the junction towards the negative electrode. The net result is that the depletion layer grows wider due to a lack of electrons and holes and presents a high impedance path, almost an insulator. The result is that a high potential barrier is created thus preventing current from flowing through the semiconductor material.

A Reverse Biased Junction showing the Increase in the Depletion Layer:

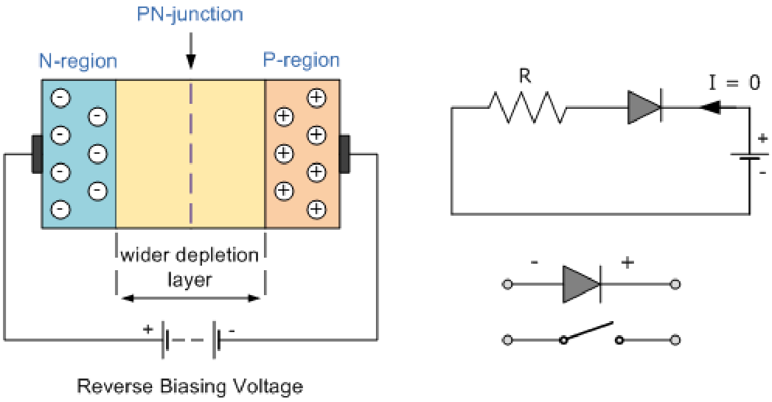

Figure 10.3:

This condition represents the high resistance direction of a PN-junction and practically zero current flows through the diode with an increase in bias voltage. However, a very small leakage current does flow through the junction which can be measured in microamperes, (A). One final point, if the reverse bias voltage Vr applied to the junction is increased to a sufficiently high enough value, it will cause the PN-junction to overheat and fail due to the avalanche effect around the junction. This may cause the diode to become shorted and will result in maximum circuit current to flow, Ohm's Law and this shown in the reverse characteristics curve below.

Reverse Characteristics Curve for a Diode:

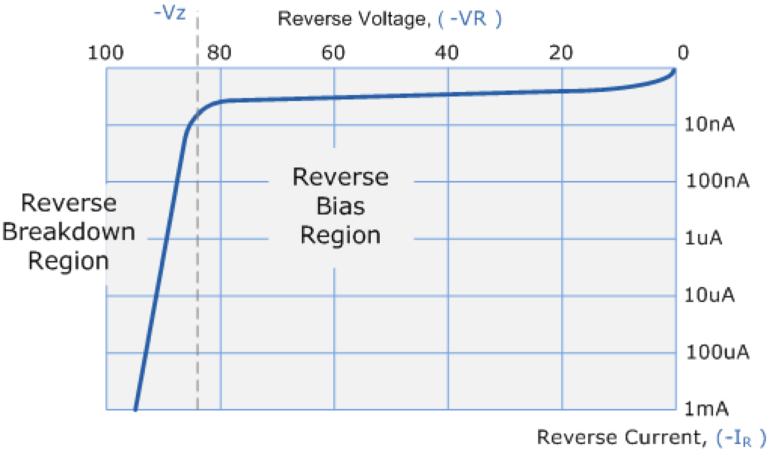

Figure 10.4:

Sometimes this avalanche effect has practical applications in voltage stabilising circuits where a series limiting resistor is used with the diode to limit this reverse breakdown current to a preset maximum value thereby producing a fixed voltage output across the diode. These types of diodes are commonly known as Zener Diodes and are discussed in a later tutorial.

Forward Bias:

When a diode is connected in a Forward Bias condition, a negative voltage is applied to the N-type material and a positive voltage is applied to the P-type material. If this external voltage becomes greater than the value of the potential barrier, 0.7 volts for Silicon and 0.3 volts for Germanium, the potential barriers opposition will be overcome and current will start to flow as the negative voltage pushes or repels electrons towards the junction giving them the energy to cross over and combine with the holes being pushed in the opposite direction towards the junction by the positive voltage. This results in a characteristics curve of zero current flowing up to this ”knee” voltage and high current flow through the diode with little increase in the external voltage as shown below.

Forward Characteristics Curve for a Diode:

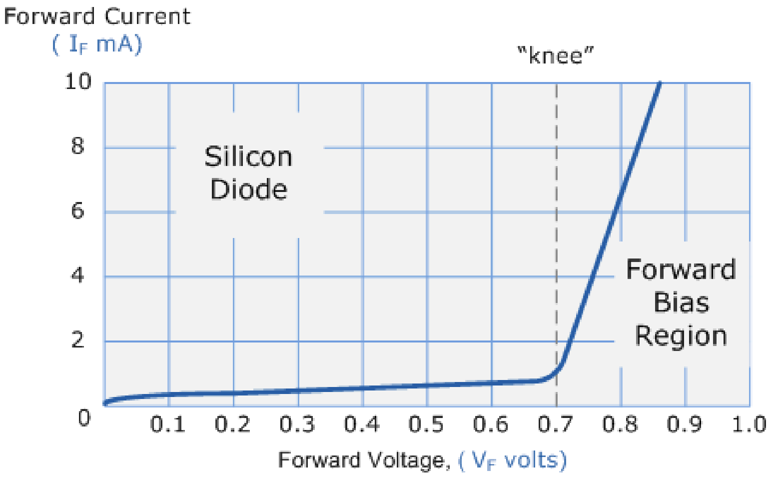

Figure 10.5:

This results in the depletion layer becoming very thin and narrow and which now represents a low impedance path thereby producing a very small potential barrier and allowing high currents to flow. The point at which this takes place is represented on the static I-V characteristics curve above as the "knee" point.

Forward Biased Junction Diode showing a Reduction in the Depletion Layer:

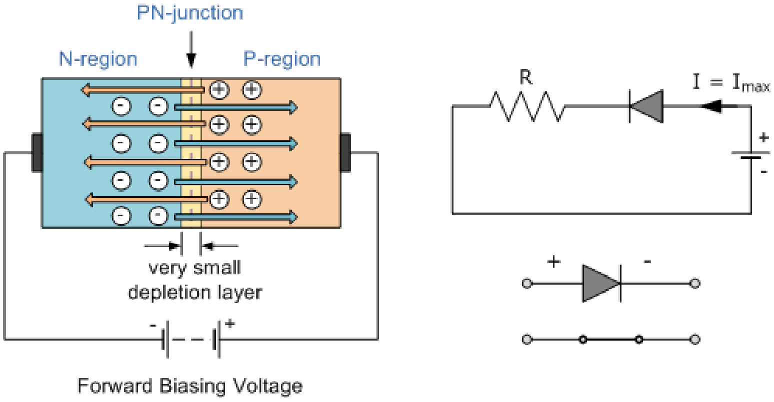

Figure 10.6:

This condition represents the low resistance direction in a PN-junction allowing very large currents to flow through the diode with only a small increase in bias voltage. The actual potential difference across the junction or diode is kept constant by the action of the depletion layer at about 0.3v for Germanium and about 0.7v for Silicon diodes. Since the diode can conduct ”infinite” current above this knee point as it effectively becomes a short circuit, resistors are used in series with the device to limit its current flow. Exceeding its maximum forward current specification causes the device to dissipate more power in the form of heat than it was designed for resulting in failure of the device.

References:

http://www.ustudy.in/node/2944

http://matse1.matse.illinois.edu

National Instruments, Labview Bookshelf

Equipments

Function Generator

Diode

Resistors

Nanovoltmeter (Keithley 2182A)

REPORT SHEET

Experiment 10: I-V CHARACTERISTICS OF SOLID STATE DEVICES

Students Name:

Experiment Date:

Group Member Name(s):

Laboratory Bench Number:

Assistants Name and Signature:

1. Plot the voltage (horizontal axis) vs. the current (vertical axis) from the resistor and diode data.

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2. What is the shape of the graph of the data for the resistor?

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3. What is the shape of the graph of the data for the diode?

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4. According to Ohm's Law, V/I represents what measurable quantity?

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5. For the graph that is nonlinear, how did the values of V/I vary as the values of V increased?

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6. Which device conducts electricity both directions?

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7. Which device conducts electricity only in one direction?

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8. Name the 2 types of charge carriers. In a metal, what conducts electricity (carries charge)? In a semiconductor, what carries charge?

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9. In a resistor, increased voltage has what effect on the charge carriers?

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10. In a diode, what changes to allow more current to flow as the voltage is increased?

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Discussion

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Chapter 11

ZEEMAN EFFECT

Purpose

The purpose of this experiment is to observe the splitting of spectral lines in a magnetic field and to determine charge to the mass ratio (e/m) of the specific elementary charge.

Introduction

The experimental observation of the quantisation of orbital angular momentum in a uniform magnetic field is called the normal Zeeman effect. The total angular momentum $\vec{J}$ of an atom is given by

$$\vec{J} = \vec{L} + \vec{S} \tag{1}$$

where $\vec{L}$ and $\vec{S}$ are the total orbital and spin angular momentum, respectively. For a single electron atom, the magnitude of $\vec{L}$ is associated with the orbital angular momentum quantum number l as

$$L = \sqrt{l(l+1)}\hbar \tag{2}$$

Assume that, the spin angular momentum of the electron is neglected, or that the total net spin is zero. Thus, the total ancular momentum is due to the orbital angular momentum of the atom. The magnetic moment of a single orbital electron of the atom is given by

$$\vec{\mu_l} = -\frac{e}{2m}\vec{L} \tag{3}$$

Here, μ_l is quantised since L is quantised. The magnetic potential energy of an atom in a magnetic field is; therefore,

$$V_m = -\vec{\mu_l}\vec{B} \tag{4}$$

when combined with Equation (3), it is given by

$$V_m = \frac{e}{2m}\vec{L}.\vec{B} \tag{5}$$

$\vec{L}.\vec{B} = LB\cos\theta$ and $L\cos\theta = L_z$, the magnetic potential energy becomes

$$V_m = (\frac{e}{2m})L_z B \tag{6}$$

since $L_z = m_l\hbar$, hence we get

$$V_m = m_l(\frac{e\hbar}{2m})B \tag{7}$$

The quantity, $\frac{e\hbar}{2m}$ is called Bohr magneton, μ_b. Since L has (2l+1)-fold degeneracy, i.e., for a given value of l, m_l can take (2l+1) different values: -l, -(l-1),...,-2,-1,0,1,2,...,(l-1),l; therefore, from Equation (7), V_m can also take (2l+1) values. Thus, a state, that is in a quantum state l with energy E_o when placed in a magnetic field, will split into (2l+1) substates with their energies given by the expression

$$E = E_o + V_m = E_o + m_l\ \mu_b B \tag{8}$$

When l = 2, m_l = -2,-1,0,1,2; E will take the following values

$$E = E_o - 2\mu_b B$$
$$E = E_o - \mu_b B$$
$$E = E_o$$
$$E = E_o + \mu_b B$$
$$E = E_o + 2\mu_b B$$

Here, it may be noted that the levels are equally spaced.

In actual practice one can not observe the resulting new levels. The only way to get information about the levels is to observe the transitions between the levels. In the absence of the magnetic field, the photon energy $h\nu_o$ is

$$h\nu_o = E_o^i - E_o^f \tag{9}$$

In a magnetic field, B, the expressions for the energies take the form

$$E^i = E_o^i + V_m^i = E_o^i + m_l^i \mu_b B \tag{10}$$

$$E^f = E_o^f + V_m^f = E_o^f + m_l^f \mu_b B \tag{11}$$

Therefore, the photon energy $h\nu$ of the transition between the initial and the final states in a magnetic field can be found by subtracting Equation (11) from Equation (10) as

$$h\nu = E^i - E^f = (E_o^i - E_o^f) + \triangle m_l \mu_b B \tag{12}$$

where $\triangle m_l = m_l^i - m_l^f$. Thus, the frequency of the transition is,

$$\nu = \nu_o + \triangle m_l \frac{eB}{4\pi m} \tag{13}$$

Due to the selection rule, only those for which the change in magnetic quantum number is 0 or ±1, i.e.,

$$\triangle m_l = 0, \pm 1 \tag{14}$$

Combining Equation (13) and (14) will show that the original transition frequency ν_o is replaced by these transitions with the following frequencies,

$$\begin{aligned} \nu &= \nu_o - \frac{e}{4\pi m} B \\ \nu &= \nu_o \\ \nu &= \nu_o + \frac{e}{4\pi m} B \end{aligned} \tag{15}$$

As an example, the normal Zeeman effect for the transition between the 5^1D_2 state and 5^1P_1 state of Cadmium (Cd) is shown in Figure 6.1

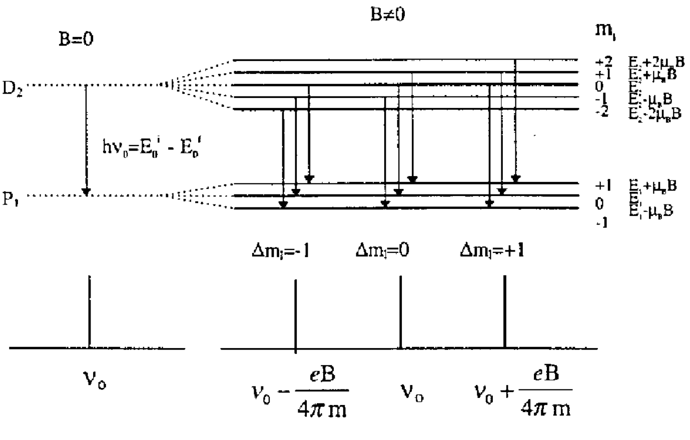

Figure 11.1: The Normal Zeeman Effect of a transition between 5^1D_2 and 5^1P_1

This specific transition gives off a red line with a wavelength of 6438 $\mathring{A}$, which is studied in our experiment. Here, it may be seen from the term symbol of these states that the total spin angular momentum is zero in both levels; therefore, the total angular momentum is purely orbital angular momentum so the transition is studied under the normal Zeeman effect.

Although there are nine transitions, the magnitudes of the separations are such that show up as only three groups of different frequencies, each containing a group of three lines. However, a doublet or a triplet is observed when the transitions are viewed in the direction parallel or perpendicular to the direction of the magnetic field .

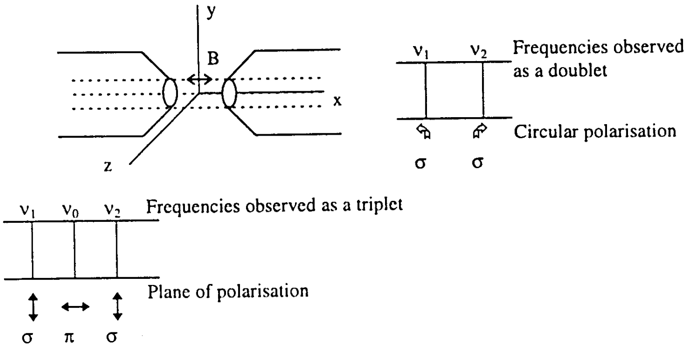

Figure 11.2: Zeeman splitting of a line when viewed in the direction parallel and perpendicular to the direction of an external magnetic field

In Figure 6.2 the abbreviation π represents the vibrations parallel to the external field $\vec{B}$ and σ represents the vibrations perpendicular to $\vec{B}$.

The nature of the light emitted in these transitions are described as follows:

1. When the Zeeman Effect is viewed along the direction of the magnetic field $\vec{B}$, only a doublet is observed. The view can be obtained through a hole in the pole face and only the two components corresponding to right-handed and left-handed circularly polarised light are observed. The right-handed components correspond to the transition $\triangle m_l = 1$ while the left-handed component correspond to $\triangle m_l = -1$. This is because, light is transverse in nature and the electromagnetic field must always have the field vectors $\vec{E}$ and $\vec{B}$ normal to the direction of propagation; thus, according to Figure 6.2, no light will be emitted in the x-direction parallel to the direction of field $\vec{B}$.

2. When the Zeeman Effect is viewed in a direction perpendicular to the direction of the magnetic field $\vec{B}$, a triplet is observed. Meanwhile, the other two lines are observed as plane polarised light with the electric field vector, which is perpendicular to the direction of the external magnetic field. Meanwhile, the third line is observed in the same position of field free line and it is the same as plane polarised light with the electric field vector of the electromagnetic wave parallel to the direction of the external magnetic field.

The polarisation values may be summarised as follows:

Viewed $\perp$ to $\vec{B}$

$\triangle m_l = \pm 1$; plane polarised $\perp$ to $\vec{B}$;σ components
$\triangle m_l = 0$; plane polarised $\perp$ to $\vec{B}$;π components

Viewed $\parallel$ to $\vec{B}$

$\triangle m_l = \pm 1$; circularly polarised ; σ components
$\triangle m_l = 0$; forbidden ; π components

The two σ-components, or outer secondaries of the triplet, or the two lines of the doublets are shifted as

$$\triangle\nu = \pm\mu_B B = \pm\frac{e}{4\pi m}B \tag{16}$$

$\triangle\nu$ may be derived from the resolution of the Lummer-Gehrcke plate as follows:

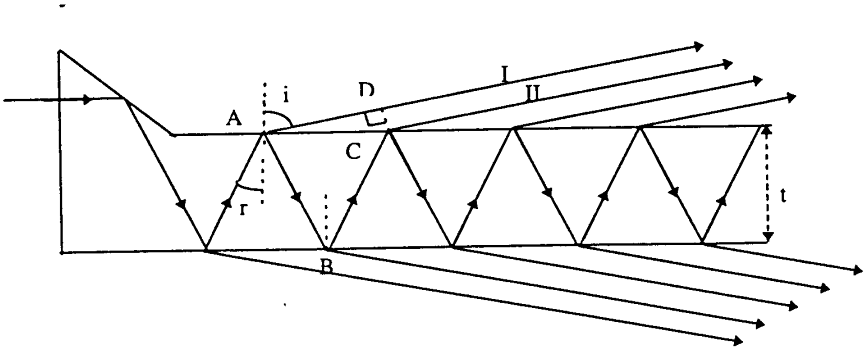

Figure 11.3: Lummer-Gehrcke Plate

The Lummer-Gehrcke plate is a kind of interferometer with high resolving power($R = \dfrac{\lambda}{\triangle\lambda} \approx 50000$). As a result, $\triangle\lambda = 0.01\mathring{A}$ is measurable from the visible displacement of a spectral line. It is a parallel plate of quartz, provided with the prism, at the left end as shown in Figure 6.3, for introducing the light. The incident light is multiply reflected internally at the plate surfaces, since both sides of the plate are coated with a thin metal providing high reflectivity, but low transmission for light. At each reflection, which is arranged to be near the critical angle, a beam emerges from the surface of the plate at an almost grazing angle. If the emerging beams are collected by a lens, the fringes are formed at the lens focus. For constructive interference, the path difference between beam I and II in the figure will be

$$\delta = \mu(\overline{AB}+\overline{BC})-\overline{AD} = n\lambda \tag{17}$$
$$\overline{AB} = \overline{BC}; \overline{AD} = \overline{AC}\cos(90-i)$$
$$\overline{AC} = 2\overline{AB}\sin r$$

$\overline{AD} = 2\overline{AB}\sin r \sin i$
and
$t = \overline{AB}\cos r$

where μ: refractive index of the quartz plate (=1.457)
n: order number
t : thickness of the plate (= 4.04mm)
i : emerging angle of the beam
r: the reflection angle

Since the relationship between i and r is:

$$\sin i = \mu \sin r \tag{18}$$

Equation (17) becomes:

$2\mu\overline{AB} - 2\overline{AB}\sin r \sin i = n\lambda$
$2\overline{AB}(\mu - \mu\sin^2 r) = n\lambda$
$2\overline{AB}\mu(\cos^2 r) = n\lambda$
$2\mu t \cos r = n\lambda$

or in terms of the angle i:

$$2t(\mu^2 - \sin^2 i)^{1/2} = n\lambda \tag{19}$$

taking the square of both sides:

$$4t^2(\mu^2 - \sin^2 i) = n^2\lambda^2 \tag{20}$$

Differentiating with respect to i gives:

$$\delta i = \frac{-n\lambda^2}{2t^2 \sin 2i}\delta n \tag{21}$$

The change in angle $\triangle i$ corresponding to a change of a single order ($\delta n = 1$) is given by:

$$\triangle i = \frac{-n\lambda^2}{2t^2 \sin 2i} = \frac{-\lambda(\mu^2 - \sin^2 i)^{1/2}}{2t \sin 2i} \tag{22}$$

since $\sin^2 i \approx 1$; then,

$$\triangle i = \frac{-\lambda(\mu^2 - 1)^{1/2}}{t \sin 2i} \tag{23}$$

The dispersion, which is the rate of i with λ is found by differentiating Equation (19) with respect to λ;

$$n^2\lambda = 2t^2[2\mu(\frac{d\mu}{d\lambda}) - \sin 2i\frac{di}{d\lambda}] \tag{24}$$

$$\frac{di}{d\lambda} = \frac{2\lambda\mu(\frac{d\mu}{d\lambda}) - 2(\mu^2 - \sin^2 i)}{\lambda \sin 2i} \tag{25}$$

The wavelength range between the successive orders is given by equating δi with $\triangle i$ which gives $\triangle\lambda$, the order separation as:

$$\triangle\lambda = \frac{\lambda^2(\mu^2 - 1)^{1/2}}{2t[\mu^2 - 1 - \mu\lambda\frac{d\mu}{d\lambda}]} \tag{26}$$

by ignoring the $\frac{d\mu}{d\lambda}$, Equation (24) becomes;

$$\triangle\lambda = \frac{\lambda^2(\mu^2 - 1)^{1/2}}{2t(\mu^2 - 1)} \tag{27}$$

In the experiment, spectral lines are always observed in several interference levels at the same time. Instead of one line, a whole system of lines appears (Figure 6.4).

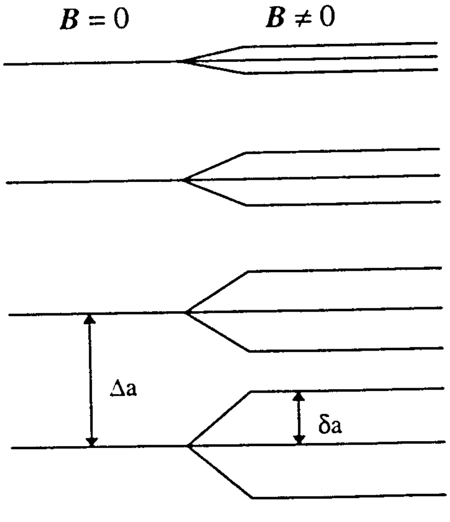

Figure 11.4: Interference lines observed in the presence of a magnetic field and without a magnetic field.

From the above figure, the distance, δa,of the splitted line from the original interference line is proportional to $\triangle a$, which is the distance between two interference lines without a magnetic field. If the change in λ is small (e.g. $\triangle\lambda$), the corresponding displacement also decreases:

$$\triangle\lambda = \frac{\delta a}{\triangle a} \triangle \lambda \tag{28}$$

with Equation (27)

$$\triangle\lambda = \frac{\delta a}{\triangle a}\frac{\lambda^2(\mu^2-1)^{1/2}}{2t(\mu^2-1)} \tag{29}$$

Since $\nu = \frac{c}{\lambda}$, the frequency shift is $\triangle\nu = \pm\frac{c}{\lambda^2}\triangle\lambda$,together with Equation (29), the frequency shift turns out to be

$$\triangle\nu = \frac{c\delta a}{\triangle a}\frac{(\mu^2-1)^{1/2}}{(\mu^2-1)} \tag{30}$$

By equating Equation (30) with (16), the $\frac{e}{m}$ value can be found as

$$\frac{e}{m} = \frac{4\pi c\delta a(\mu^2-1)^{1/2}}{2tB \triangle a(\mu^2-1)} \tag{31}$$

The picture and schematic diagram of the Zeeman Effect experiment are shown in Figure 6.5. The necessary magnetic field is produced by an electromagnet. For the fixed spacing, between the poles of the magnet, the magnetic field strengths associated with the currents passing through the coils are given in Table 6.1.

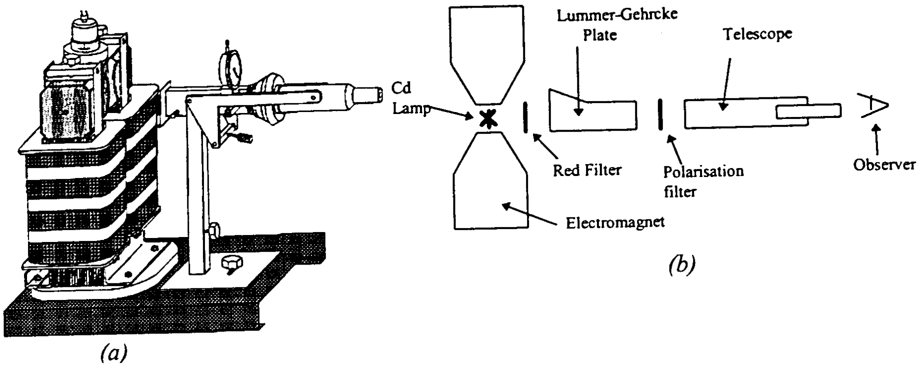

Figure 11.5: (a) Picture of the setup and (b) the schematic diagram of the Zeeman Effect experiment

Table 6.1 Magnetic field strength associated with a current passing through the coils.

I [A]	B [T]
2.0	0.050
4.0	0.105
6.0	0.163
8.0	0.223
10.0	0.279
12.0	0.336
14.0	0.421
16.0	0.445
18.0	0.494

Although the information given above describes the Zeeman splitting in both cases; when viewed parallel and perpendicular to the direction of the external magnetic field, you will carry out the experiment only by viewing the spectra in the direction perpendicular to the direction of the magnetic field.

Equipments

A cadmium lamp with holder,
An electromagnet,
A red filter,
Lummer-Gehrcke plate,
A polarization filter
A telescope.

Procedure

1. Turn the cadmium lamp on. It takes about 5 minutes for the red Cd line to be emitted sufficiently strong.

2. For pre-adjustment, remove the eyepiece. Turn the whole optical system in a clock-wise direction until a fine straight pattern can be seen on the Lummer-Gehrcke plate.

3. Adjust the height of the Lummer-Gehrcke plate until it reaches the Cd lamp (screw it to the base of the column of the optical system).

4. Set the position of the incident window relative to the Lummer-Gehrcke plate; to do this, loosen the covering cup, either lift or lower these and then tighten the knurled screws again.

5. Repeat steps 3 to 5 until a bright and clear line pattern is seen above and underneath the Lummer-Gehrcke plate.

6. Put the eyepiece back in, and by moving the eyepiece, focus the spectral line. Focus the graticule by turning the eyepiece.

7. To measure the line pattern and the distance, $\triangle a$, between them in the absence of a magnetic field, align the cross-hair in the eyepiece with any line you have chosen, and set the micrometer clockwork to an initial reference value.

8. By turning the screw at the bottom of the clockwork, align the cross in the eyepiece with the next line and then read the distance, $\triangle a$, on the micrometer clockwork relative to the reference value. Record it in Table 6.2.

9. Turn on the power supply unit of the electromagnet in order to observe the Zeeman splitting of the lines. Set the coil current of the magnet to 19A, observe the splitting of the lines into three components.

Note: Before turning on the magnetic current, make sure that the poles of the magnet are firmly screwed on. When the magnetic field is turned on, do not come close to the spectral lamp with ferromagnetic objects. Treat the Lummer-Gehrcke plate very carefully so that the smooth surface of 1/100 mm remains intact.

10. Take one triplet that you can see clearly, but do not lose the position of that triplet until the experiment is over.

Note: Since the lines generated by the Lummer-Gehrcke plate are not equidistant (Figure 6.4), $\triangle a$ and δa distances must be measured on the same triplet.

11. Align the cross in the eyepiece with the lower component of the triplet, and then take the micrometer clockwork position as a reference point. By going through the upper component of the triplet, measure the distance 2δa relative to the reference point obtained before. Record it in Table 6.2.

12.Repeat step 11 to obtain, 2δa, for lower values of the current passing through the coil. And then, tabulate your data on Table 6.2. It will be necessary to observe the decrease in splitting, since the magnetic field strength is directly proportional to the splitting distance, or in other words, to the frequency shift.

13. Plot a graph of $\dfrac{\delta a}{\triangle a}$ vs B. Obtain the worst and best lines for this plot, and then find the slopes of these lines. Show your calculations and report them in the space below Table 6.2.

14. Using the slope of the best line, find the ratio. Show your calculations and record them in the space below Table 6.2.

15. Using the slopes of the worst and best lines, calculate your error in (e/m). Record it in the space below Table 6.2.

16. Obtain the magnetic field strengths from the corresponding currents passing through the magnet by interpolating the data in Table 6.1. Record them in Table 6.2.

REPORT SHEET

EXPERIMENT 11: ZEEMAN EFFECT

Student's Name:
Experiment Date:
Group Member Name(s):
Laboratory Bench Number:
Assistant's Name and Signature:

Data and Calculations

Table 6.2 Splitting of a spectral line under various magnetic field strengths.

Spacing between successive lines without a magnetic field
$\triangle a =$ ....mm

I[A]	B[T]	2δa [x10^{-2} mm]	δa[x10^{-2} mm]	$\delta a/\triangle a$
19				
18				
17				
16				
15				
14				
13				
12				
11				
10				

I ; Magnet Current
B ; Magnetic Field Strength
2δa ; Spacing between 2 extreme lines
δa ; Spacing between successive lines

The slope of the best line = ...
The slope of the worst line =...................

$(\frac{e}{m})$=.............

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$\triangle(\frac{e}{m})$=..............

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Questions

1. What is the most important general statement you can make after performing this experiment?

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2. What do you think the spectral lines may correspond to?

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3. In the measurement of the splitting, you measured 2δa instead of δa. Does this make any sense? Why?

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Discussion

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Chapter 12

KERR EFFECT

Introduction

Monochromatic, vertically polarized light impinges on a PLZT element (lead-lanthanum-zirconium-titanium compount) which is set in its holder at 45^o to the vertical. An electric field is applied to the PLZT element and causes it to become birefractive. The phase-shift between the normal and the extraordinary light beam behind the PLZT element is recorded as a function of the applied voltage and it is shown that the phase-shift is proportional to the square of the electric field strength respectively of the voltage applied. From the constant of proportionality the Kerr constant is calculated for the PLZT element.

The Kerr effect has usually been demonstrated with nitrobenzene in the past. Since nitrobenzene is very toxic and needs high voltages of some kV the PLZT element which only needs some hundred volts represents an attractive alternative.

The light wave, whose electric field vector oscillates parallel to the external electric field, is called the extraordinary beam whereas the wave oscillating perpendicular to the field is known as the normal beam.

If the corresponding refractive indices are designated by n_{ao} and n_o and ℓ is the distance in the PLZT element covered by the light, then there is a difference in optical paths for the two waves of

$$\ell(n_{ao} - n_o)$$

This corresponds to a phase displacement of

$$\triangle = 2\pi\frac{\ell}{\lambda}(n_{ao} - n_o) \tag{1}$$

where λ is the wavelength of the light in vacuum. (here $\lambda = 633$ nm)

It can also be shown that the phase displacement is proportional to length ℓ and the square of polarization P. If we anticipate that the polarization is a linear function of the electric field strength E and the proportionality factor is designated by $2\pi K$, then the following relations obtained:

$$\triangle = 2\pi K\ell E^2 \tag{2}$$

K is the Kerr constant.

E can be expressed by the applied voltage U and the interelectrode distance d

$$E = \frac{U}{d} \tag{3}$$

The luminous intensity I behind the analyser is obtained for the given experimental apparatus (polarizer and analyser crossed and at 45^o to the electric field on the PLZT element) from the relationship (1)

$$I = I_o \sin^2 \frac{\triangle}{2} \tag{4}$$

I_o is the luminous behind the analyser when the polarizer and the analyser are aligned in the same direction and the electric field on the PLZT element is zero. After substituting (2) in (4) and using (3), the followings is obtained:

$$I = I_o \sin^2 \frac{\pi K\ell U^2}{d^2} \tag{5}$$

Solving the equation for U^2 gives:

$$U^2 = \frac{d^2}{\pi K\ell} arc \sin \sqrt{I/I_o} \tag{6}$$

Related Topics:

Polarization of light, birefraction, optical anisotropy, modulation of light, electro-optical modulator, PLZT-element.

Equipments

Kerr cell, PLZT-element
High voltage supply unit, 0-10 kV
Laser, He-Ne 1.0 mw, 220 V AC
Polarising filter, on stem
Optical profile bench l=60 cm
Base f.opt.profile-bench, adjust.

Slide mount f.opt.pr.-bench, h 30 mm
Photoelement f. opt. base pit
Universal measuring amplifier
Digital multimeter
Screened cable, BNC, 1750 mm
Adapter, BNC-socket/4 mm plug pair
Connecting cord, 750 mm, red
Connecting cord, 750 mm, blue
OPTION for electro-optical modulator
Power frequency generator 1 MHz
Loudspeaker, 8 ohm/5 kohm

Procedure

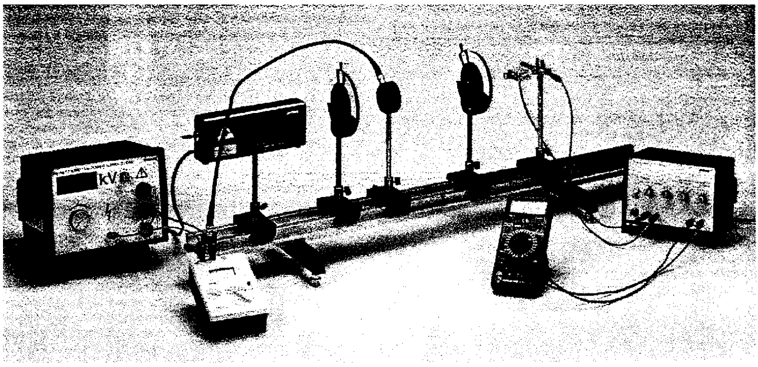

Figure 12.1: Experimental setup for demonstrating the Kerr effect

The experiment for the demonstration of the Kerr effect is set up as shown in Figure 9.1. The PLZT element is connected directly to the HV power supply whose voltage can be altered between 0 and 1000 Volt with a sufficiently high precision by using a digital voltmeter branched in parallel to the HV power supply. **Do not exceed 1000 V, this will damage the PLZT element.** The light source is a He/Ne laser, the power of which is 1 mW.

Important: Before performing any measurement of luminous intensity the He/Ne laser has to be switched on for about one hour to reach its equilibrium in power emission. Moreover, after each appreciable variation of the voltage applied to the PLZT element about five minutes have to elapse before the crystal structure has readapted and a representative luminous intensity reading can be taken. Needless to say, all measurements have to be performed in a darkened room. The nonpolarized portion of the light (background radiation) must also be taken into account. The mesured values depend on the history of the PLZT-element. Also the number of detectable maxima may vary for different elements.

Caution: Never look directly into a non attenuated laser beam

As can be seen from Figure 9.1, the light from the He/Ne laser, which is vertically polarized on passing through the polarizer, impinges on the PLZT element which is set in its holder at 45^o to the vertical. The incident linearly polarized wave can be regarded as the superimposition of two 'in phase' oscillating waves which are polarized, one perpendicularly and the other parallel, to the PLZT element and to the electric field that is applied to the PLZT element.

The two light waves pass through the PLZT element at different speeds. The light wave which oscillates parallel to the electric field of the PLZT element is delayed relative to the light wave which oscillates perpendicularly to the applied electric field of the PLZT element. This produces a phase difference between the two waves and the light which has passed through the Kerr cell (PLZT element) will be elliptically polarized. This results in the analyser, which is located behind the Kerr cell at 90^o to the polarizer, no longer being able to extinguish the polarized light.

For a phase difference between the two waves of $\lambda/2$ a linear polarized wave results from the superimposition of the two waves after they have passed through the PLZT element. This linearly polarized wave is turned by 90^o with respect to the direction of incidence, e.g. with respect to the vertical. The applied voltage is therefore called the 'half-wave voltage'. In this case the light intensity behind the analyser which is at an angle of 90^o to the polarizer will show a maximum. A silicon photodiode with amplifier is used as the detector for the luminous intensity behind the analyser.

As long ago as 1875 Kerr discovered that a glass plate to which a strong electric field was applied became birefractive. It soon became clear that this effect was not based on deformation caused by the electric field as the same phenomenon was observed in liquids and even in gases.

The PLZT element used in this experiment has the advantage that the birefraction, represented by the Kerr constant, is more than two orders of magnitude larger than for nitrobenzene and voltages of a few hundred volts are sufficient in order to study the electro-optical effects of the ceramic element. This one is transparent for wavelengths from 0.4 to 5.6 μm. Its chemical compositions here described by the formula Pb 0.9125, La 0.0875, Zr 0.65, Ti 0.3503. With regard to the transmission of light the PLZT element behaves like a transparent polycrystal. For $\lambda = 633$ nm its transition ratio is more than 60%. With respect to an applied electric field, it behaves like a ferromagnetic substance which is submitted to a magnetic field.

Within the PLZT element there are already prepolarized domains which grow or which are reorientated by the applied electric field. In this way, the element becomes optically anisotropic respectively birefractive. Regarding the above mentioned electro-optical modulation, it should be pointed out that the element can deal with modulation frequencies of up to 100 kHz.

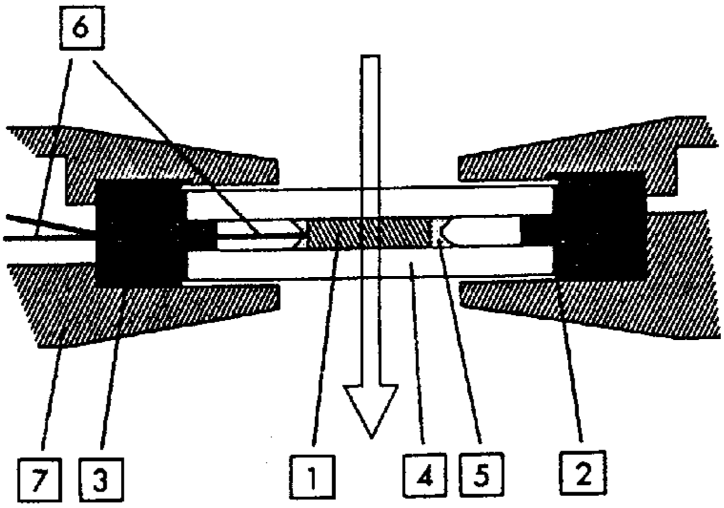

Figure 12.2:

Figure 9.2 shows a cross-section of the PLZT element. The active element (1) of the modulator is a parallelpiped of height = 8 mm, length = 1.5 mm and width = 1.4 mm.

The width represents the distance between the electrodes. The electric field strength is given by the ratio of voltage applied over the distance between the electrodes. The path of the light beam within the element is equal to the length of the element. Active element (1) is encapsulated using silicon hermetics (2) an isolating ring (3) and glued between two glass plates (4). As optical glue (5) Canadian balsam was used. Wire (6) are fixed on the electrode faces of the element and connected with BNC socket on frame (7).

Option: Electro-optical modulator

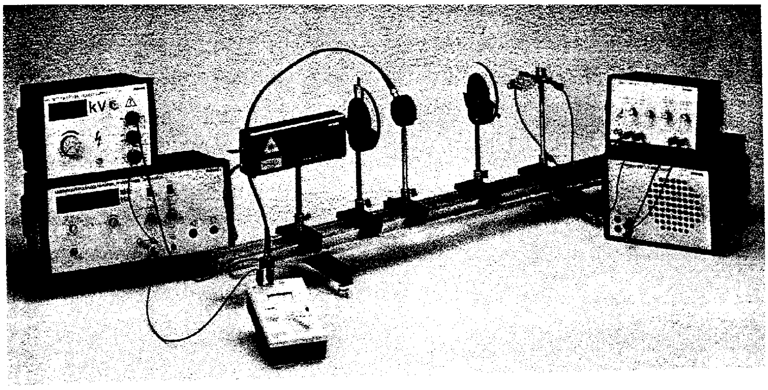

Figure 12.3: Setup for electro-optical modulator

By superposition of an AC-voltage onto the constant electric field the PLZT element is changed into an electro-optical modulator whose functioning is demonstrated acoustically by using an AC-voltage of variable frequency within the audible range.

The output of the power frequency generator is connected in series with a DC voltage of 500 V. The modulated DC voltage is applied to the PLZT element. The voltmeter at the output of the universal amplifier is replaced by a loudspeaker. The output of the universal amplifier (amplification $V = 10^2$) is connected to the 5 Kohm input of the loudspeaker. The amplitude of the frequency generator should be adjusted such that a noise-free sound is heard at the loudspeaker.

By altering the frequency of the generator around 1 kHz, the property of the PLZT element as an electro-optical modulator can be convincingly demonstrated.

REPORT SHEET

EXPERIMENT 12: KERR EFFECT

Student's Name:
Experiment Date:
Group Member Name(s):
Laboratory Bench Number:
Assistant's Name and Signature:

Data and Calculations

Table 9.1

U(V)	I	I/I_o	$\triangle/2 = arc\sin\sqrt{I/I_o}$
300			
350			
400			
450			
500			
550			
600			
650			
700			
750			
800			
850			
900			
950			
1000			

By plotting U^2 against $2arc\sin\sqrt{I/I_o}$ an approximately straight line is obtained and the Kerr constant can be derived from its slope, because the geometrical dimensions ℓ and d for the Kerr cell (PLZT element) are known.

1. Measure the relative luminous intensity, I/I_o, behind the analyser as a function of the voltage U applied to the PLZT element.

Fill out Table 9.1. Plot I/I_o versus U. When the luminous intensity reaches a maximum for the first time, the normal and extraordinary beam are phase-shifted by 180 ^{o}. This voltage is therefore the 'half-wave voltage'. It is a function at the PLZT element composition and of the temperature. Indicate half voltage on the graphic.

2. Plot the square of the voltage applied to the PLZT element as a function of the phase-shift between normal and extraordinary beam. By linear regression a straight line has to be found whose slope has to be used to find Kerr contant, where $\ell = 1.5$ mm and $d = 1.4$ mm

Note : Kerr constant value may vary for different histories and different elements.

Discussion

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Chapter 13

COMPTON EFFECT

Purpose

To determine the Compton wavelength by meauring the energy of scattered γ-radiation as a function of the angle of scatter.

Introduction

The collision of a photon or a γ-quantum with a free electron which gives rise to a directional change of the γ-quantum is called Compton scattering. From the laws of conservation of energy and momentum, the wavelength of the γ-quantum will be increased. This change of wavelength is dependent upon the angle of scatter and is given by the expression:

$\triangle\lambda = \lambda_c(1 - \cos\Phi)$,

where

$$\lambda_c = \frac{h}{mc}$$

is the Compton wavelength of the electron, h is Planck's constant, m is the rest mass of the electron, and c is the velocity of light. Φ is the angle between the the incident and scattered wave.

Related Topics:

Corpuscle, scattering, Compton wavelength, γ-quanta, de Broglie wavelength, Klein-Nishina formula.

Equipments

Americium-241 source, 370 kBq

Radioactive source, Na-22, 74 kBq

Source Cs-137, 37 kBq
Radioactive source, Cs-137,18.5 MBq
Gamma detector
Operating unit f. gamma detector
Screen. cylinder f. gamma detector
High-voftage connecting cable
Rod, iron, d 25 mm, 1200 mm
Impulse height analyser
Oscilloscope, 20 MHz, 2 channels
xyt recorder
Lead block, 200x100x50 mm
Lead brick with hole
Source holder on fixing magnet
Screened cable, BNC, 1750 mm
Connecting cord, 750 mm, red
Connecting cord, 750 mm, blue

Procedure

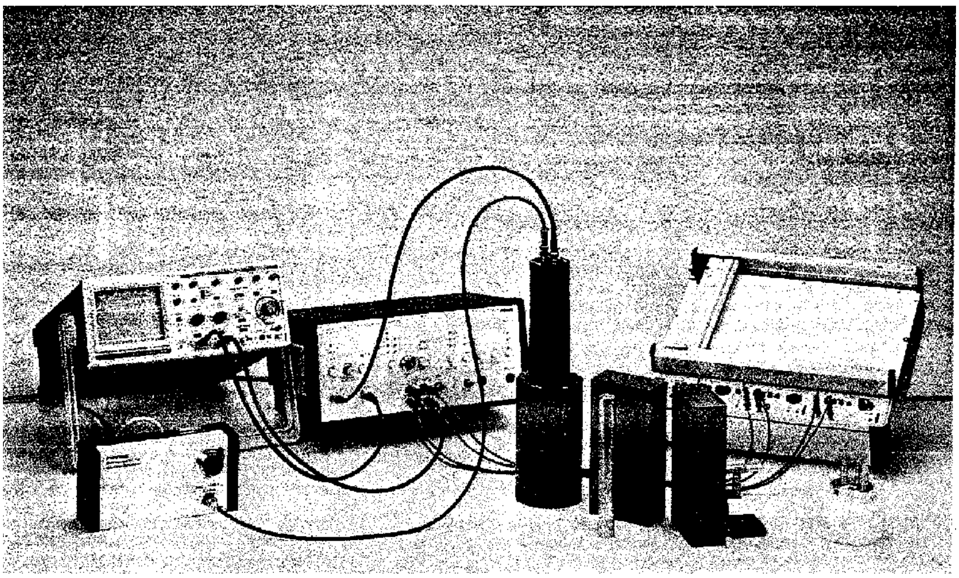

Figure 13.1: Experimental setup studying the Compton effect

Set up the apparatus as shown in Figure 10.1

The NaI scintillation detector is a highly sensitive instrument and must be treated with care. In particular, avoid mechanical impacts and large changes of temperature. The working instrument for the detector may be switched on only **after** the detector has been connected.

1. To calibrate the measuring set-up, stick the pellet-shaped Cs-137 source directly in front of the inlet opening using a piece of adhesive tape. Set the detector operating voltage initially to 8.00. Pulses will now be seen on the oscilloscope. Adjust the amplification factor on the pulse height analyser so that the clearly visible 661 keV pulses attain an amplitude to about 9 V_{pp}. Sometimes it may be neccesary to alter the detector operating voltage.

Set the window width on the pulse height analyser to 5% and select the operating mode 'Main'.

Using the knob marked 'Basis', now search for the 661 keV peak on the xyt recorder (xyt recorder sensitivity x:appox. 10 mV/cm; y:approx. 500 mV/cm). Position the pen on the right-hand edge of the 661 keV peak using the 'Basis' knob, and then adjust the x-sensitivity of the xyt recorder so that the pen is situated approximately on the right-hand end of the recording sheet. Then switch to automatic operation and keep the 'Null' button depressed. Now, using the zero adjuster of the xyt recorder, position the pen on the starting point on the left-hand side of the recording sheet.

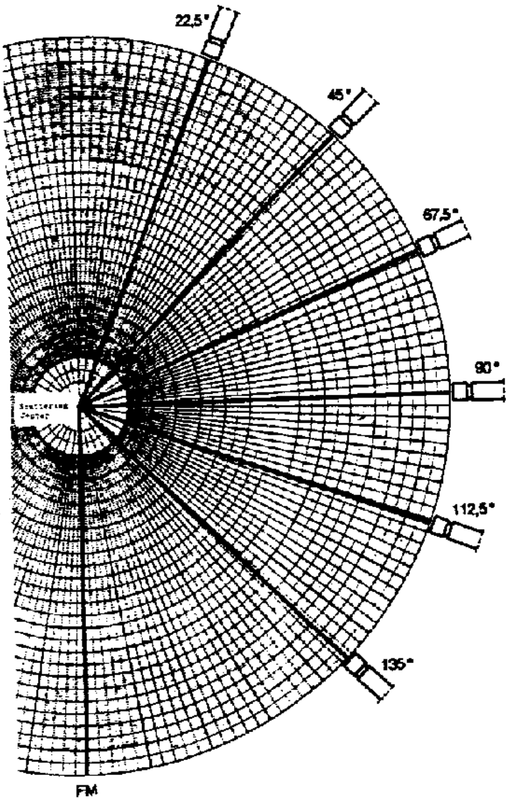

Figure 13.2: Polar diagram for geometrical arrangement of detector,scattering medium and source

Once the setting has been made, the detector voltage, basis, amplification and x-sensitivity may not be altered.

For the energy calibration of the set-up, record the 661.6 keV line of Cs-137 and (at higher y-sensitivity) the 32 keV line of Cs-137, the 59.6 keV line of Am-241 and the 511 keV line of Na-22 using automatic operation (clock 0.8 s).

2. For the measurements it is recommended to prepare a diagram corresponding to that shown in Figure 10.2. Place the diagram on the surface of the table and arrange the source, the sub- stance used to scatter the γ-radiation, and the detector on top of the diagram at the appropriate angle. Push the source into the opening of the lead brick to about the centre.

As additional shielding from direct radiation, place an extra lead brick between the source and the detector, and arrange it in such a way that direct radiation has as long a path as possible in the lead.

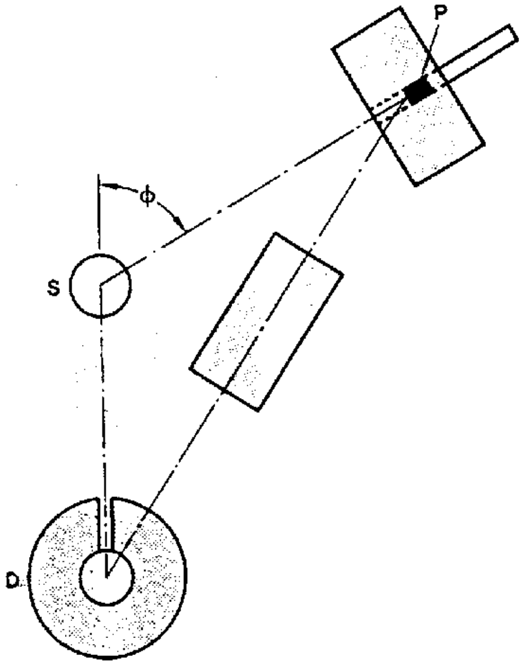

Figure 13.3: Arrangement of the extra lead brick for shielding direct radiation(P=source, S=scattering medium, D=detector)

The positioning of the lead brick is crucial, in that Compton scattering also occurs in the lead. If necessary, try out several positions.

During the experiment ensure that no other sources are situated in the immediate vincinity of the detector, or even further away from it. Since only the Compton peak is of interest, other regions can be skipped over using the 'Vorlauf' (= Foreward Run)button. However, it is important to mark the zero point for every trace (for subsequent evaluation).

It is recommended to repeat all the angular settings several times. The small angles 22.5^o and 45^o are especially crucial.

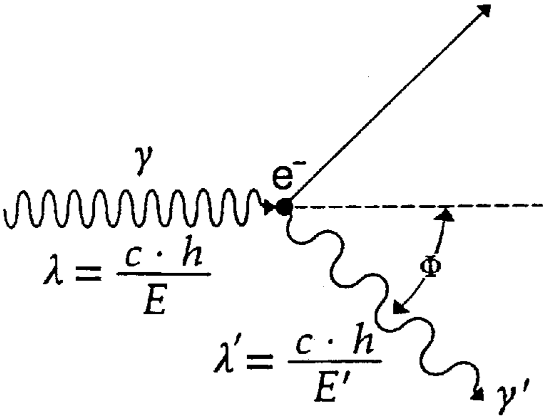

Figure 13.4: Change of wavelength during Compton collision

REPORT SHEET

EXPERIMENT 13: COMPTON EFFECT

Student's Name:
Experiment Date:
Group Member Name(s):
Laboratory Bench Number:
Assistant's Name and Signature:

Data and Calculations

1. The set-up is calibrated by recording peaks of known energy: Cs-137, Am-241 and Na-22. Plot the energies on a graph as a function of the position of the xyt recorder (x).

Determine the slope either graphically or by linear regression with the expression $E = a + bx$.

2. Determine the line centre of the measured scattering peaks graphically and, taking the calibration factor b and the distance s from the origin, calculate the energy $E = sb$ in each case. Calculate the de Broglie wavelength for the individual energies using the expression

$$\lambda = \frac{hc}{E}$$

$h = 6.625 \text{ x } 10^{-34} Ws^2$
$c = 2.997 \text{ x } 10^{8} ms^{-1}$
$1keV = 1.602 \text{ x } 10^{-16} Ws$

3. From the difference of wavelength $\triangle\lambda = \lambda' - \lambda$,($\lambda = 1.873 \text{ x } 10^{-12} m \cong 661.6$ keV), calculate the Compton wavelength for each angle as Φ

$$\lambda' = \frac{\triangle\lambda}{1 - \cos\Phi}$$

Discussion

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