# Advanced Lab

## Modern Physics (PHYS 3282)

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**The Oscilloscope**

The oscilloscope (sometimes abbreviated CRO, for cathode-ray oscilloscope) is electronic test equipment allows signal voltages to be viewed as a two-dimensional graph voltage versus time (vertical scale voltage and horizontal scale time).

**What is an oscilloscope used to measure?**

It measures two things:

1- **Voltage**.
2- **Time** (often, **frequency** [1/T])

An **electron beam** is swept across a phosphorescent screen horizontally (X direction Time proportional to X) at a known rate (perhaps one sweep per millisecond). An **input signal** is used to change the position of the beam in the Y direction (amplitude. The trace left behind can be used to measure the voltage of the input signal (off the Y axis) and the duration or frequency can be read off the X axis.

**How it works?**

The simplest type of oscilloscope consists of a cathode ray tube (CRT), a vertical amplifier, a time base generator, a horizontal amplifier and a power supply. These type oscilloscopes are now called 'analogue' scopes to distinguish them from the modern 'digital' scopes that became common.

**The cathode ray tube**

It is an evacuated glass housing/tube with its flat face covered in a phosphorescent material (emits light when electrons strike at the surface). In the neck of the tube is an “electron-gun”, which is a heated metal plate with a wire mesh (the grid) in front of it. A positive voltage is applied to accelerate the electron beam to a very high speed. When the beam hits the screen the kinetic energy of the electrons is converted by the phosphor into visible light at the point of impact. When switched on (with no sweep voltage), a CRT normally displays a single bright dot in the center of the screen.

**The interior of a cathode-ray tube**

1. Deflection electrodes
2. Electron gun
3. Electron beam
4. Focusing coil
5. Phosphor-coated inner side of the screen.
The electron beam and hence the dot can be moved up and down, left and right using electrostatic deflection plates.

A potential difference of at least several hundred volts is applied to make the heated plate (the cathode) negatively charged relative to the deflection plates.

Between the electron gun and the screen are two opposed pairs of metal plates called the deflection plates. The vertical amplifier generates a potential difference across one pair of plates, giving rise to a vertical electric field through which the electron beam passes. When the plate potentials are the same, the beam is not deflected. When the top plate is positive with respect to the bottom plate, the beam is deflected upwards; when the field (voltage/distance) is reversed, the beam is deflected downwards. The horizontal amplifier does a similar job with the other pair of deflection plates, causing the beam to move left or right. This deflection system is called electrostatic deflection.

A high positive post-deflection acceleration voltage of over 10,000 volts is often used, increasing the energy (speed) of the electron-beam that strikes the phosphor coated screen which also has scale and reticules.

**The time-base generator:**

It is an electronic circuit that generates a ramp voltage. This is a voltage that changes continuously and linearly with time. When it reaches a predefined value (<10% Ea) the ramp is reset, with the voltage reestablishing its initial value. When a trigger event is recognized the reset is released, allowing the ramp to increase again.

The simplest time base generator is a charging discharging R-C circuit with variable values of R and C as shown in figure (A). S1 is an electronic switch controlled by the trigger signal. It allows the capacitor C to charge through a very high resistance (nearly linearly increasing voltage) then discharge through a very small resistance (Very small fall time). A typical output signal is shown in figure (B).

**The horizontal amplifier:**

The time-base voltage usually drives the horizontal amplifier. Its effect is to sweep the electron beam at constant speed from left to right across the screen, and then quickly return the beam to the left in time to begin the next sweep. During the fall time a small negative potential is applied to the grid of the electron gun to block the electrons from being accelerated and then the electron beam is turned off. Gain of the horizontal amplifier is adjusted to match the sweep time of the “time-base” and the period of the
measured signal and then a fixed signal is plotted on the CRT and to calibrate the scale of the horizontal axis to measure the time.

**The vertical amplifier:**

It is driven by an external voltage (the vertical input) that is taken from the circuit or experiment that is being measured. The amplifier has very high input impedance, typically one meg-ohm, so that it draws only a tiny current from the signal source. The amplifier drives the vertical deflection plates with a voltage that is proportional to the vertical input. The gain of the vertical amplifier can be adjusted to suit the amplitude of the input voltage. A positive input voltage bends the electron beam upwards, and a negative voltage bends it downwards, so that the vertical deflection of the dot shows the value of the input. The response of this system is much faster than that of mechanical measuring devices such as the multi-meter, where the inertia of the pointer slows down its response to the input.

When all these components work together, the result is a bright trace on the screen that represents a graph of voltage against time. Voltage is on the vertical axis, and time on the horizontal.

**Inputs**

The signal to be measured is fed to one of the input connectors, which is usually a coaxial connector such as a BNC or a special cable called a 'scope probe', supplied with the oscilloscope.

The input is coupled to the vertical amplifier through a DC coupling circuit, an AC coupling circuit (prevents DC voltage) or connected to ground (zero input). This is obtained using the input control switch.

**The trace**

If no input signal is applied, the oscilloscope repeatedly draws a horizontal line called the trace across the middle of the screen from left to right. One of the controls, the time-base control, sets the speed at which the line is drawn, and is calibrated in seconds per division. If the input voltage departs from zero, the trace is deflected either upwards or downwards. Another control, the vertical control, sets the scale of the vertical deflection, and is calibrated in volts per division. The resulting trace is a graph of voltage vs. time.

**Trigger**

To provide a more stable trace, modern oscilloscopes have a function called the trigger. When using triggering, the scope will pause each time the sweep reaches the extreme right side of the screen. The scope then waits for a specified event before drawing the next trace. The trigger event is usually the input waveform reaching some
user-specified threshold voltage in the specified direction (going positive or going negative). The effect is to resynchronize the time-base to the input signal, preventing horizontal drift of the trace. In this way, triggering allows the display of periodic signals such as sine waves and square waves.

**Types of trigger include:**

**External trigger,** a pulse from an external source connected to a dedicated input on the scope.

**Internal (edge) trigger,** an edge-detector that generates a pulse when the input signal crosses a specified threshold voltage in a specified direction.

**The X-Y mode**

Most modern oscilloscopes have several inputs for voltages, and thus can be used to plot one varying voltage versus another. This is especially useful for graphing I-V curves (current versus voltage characteristics) for electronic components such as diodes, as well as Lissajous patterns. Lissajous figures are an example of how an oscilloscope can be used to track phase differences between multiple input signals.

**Dual beam oscilloscope**

A dual beam oscilloscope was a type of oscilloscope once used to compare one signal with another. It simultaneously produces two separate electron beams, capturing the entirety of two signals A and B. Two independent pairs of vertical plates deflect each of the two beams. On some scopes the time base, horizontal plates and horizontal amplifier were common to both beams; on more elaborate scopes there were two independent time bases, two sets of horizontal plates and horizontal amplifiers
**Digital storage oscilloscope**

A digital storage oscilloscope (DSO) for short is now the preferred type for most industrial applications which can store data as long as required. It also allows complex processing of the signal by high-speed digital signal processing circuits.

The vertical input, instead of driving the vertical amplifier, is digitized by an analog to digital (A/D) converter to create a data set that is stored in the memory of a microprocessor. The data set is processed and then sent to the display, which in early DSOs was a cathode ray tube, but is now more likely to be an LCD flat panel.

The screen image can be directly recorded on paper by means of an attached printer or plotter. The scope's own signal analysis software can extract many useful time-domain features (e.g. rise time, pulse width, amplitude), frequency spectra, histograms and statistics, persistence maps, and a large number of parameters meaningful to engineers in specialized fields such as telecommunications, disk drive analysis and power electronics.

Digital storage also makes possible another unique type of oscilloscope, the equivalent-time sample scope. Instead of taking consecutive samples after the trigger event, only one sample is taken. However, the oscilloscope is able to vary its time-base to precisely time its sample, thus building up the picture of the signal over the subsequent repeats of the signal.

**The Oscilloscope Calibration:**

The front panel of most modern oscilloscopes has a standard output used to calibrate the vertical and horizontal amplifiers for voltage and time respectively. In most of them this output is a TTL output pulses (5.0 V peak to peak pulses) with 1.0 KHz frequency.

This output is connected to input of each channels. The standard 5.0 V is used to calibrate the vertical scales and the 1.0 ms periodic time is used to calibrate the horizontal (time) scale.

**PC-based Oscilloscope (PCO)**

Although most people think of an oscilloscope as a self-contained instrument in a box, a new type of "oscilloscope" is emerging that consists of a specialized signal acquisition board (which can be an external USB or Parallel port device, or an internal add-on PCI or ISA card). The hardware itself usually consists of an electrical interface providing insulation and automatic gain controls, several hi-speed analogue-to-digital converters. The PC provides the display, control interface, disc storage, networking and often the electrical power for the acquisition hardware.
Experimental apparatus:
1- A dual-beam analogue scope.
2- Flashlight battery and/or low voltage power supply.
3- Two signal generators for sine and square waveforms.
4- Two BNC cables, adaptors, connecting wires.
5- PC with 750 Pasco Interface and Data Studio Software.

Experiments:

I- Check the Calibration of your scope:
1- Switch the oscilloscope with the vertical mode control on Channel A (CHA) and the horizontal mode control on X-Y mode.
2- Use the operation of the focus, intensity, horizontal position, and vertical position controls to obtain a stationary, focused spot at the center of the screen.
3- Change the horizontal mode control to a time base signal with time scale 1ms/cm. The trace will be converted into a horizontal straight line nearly at the center of the screen. Readjust the intensity, focus and horizontal position to obtain a sharp clear straight line covering the whole width of the screen.
4- Set CHA control to Ground (To ensure 0.0V input to channel 1), and readjust the vertical position of zero.
5- Change CHA control to DC and then adjust the vertical amplifier sensitivity to 1.0 V/div (usually 1 cm).
6- Use the oscilloscope probe to connect the calibrating signal to CHA. The trace should be square pulses of height of 1cm on the vertical scale and periodic time of 1 cm in the horizontal scale.
7- If not; use fine adjustment of the horizontal and vertical amplifiers to calibrate CHA.
8- Repeat steps 4-7 to calibrate CHB.

II- Measuring DC voltages:
1- Set CHA control to DC coupling and sensitivity to 1.0V/cm.
2- Connect the flashlight battery to the CH1 input. What happen to the trace?
3- Reverse the polarity of the battery and repeat.
4- Change the vertical sensitivity to 0.5 V/cm, 0.2 V/cm and repeat. Write your comments.
5- What is the advantage of using the oscilloscope to measure the terminal voltage of the battery?
6- Replace the battery by the low voltage power supply. Measure different DC voltages. (0-10 V).
7- Repeat the experiment with CHA control to AC coupling. What are your comments
8- Repeat steps 1-7 with the horizontal control to “X-Y” mode, write your observation.
9- Connect the battery (then the DC power supply) to horizontal input. What are your comments? Can you improve horizontal amplifier sensitivity?
III- **Measuring AC voltage signals:**

1. Set CHA control to AC coupling and sensitivity to 1.0V/cm.
2. Adjust the signal generator to sinusoidal output at 1 kHz. Connect the output to CHA (use the scope probe or a coaxial cable with PNC connector).
3. Adjust ‘triggering control’ to internal, CHA (this means the scope internally uses the input of CHA for triggering).
4. Adjust the time-base control to see a clear and stable trace on the screen.
5. Use the scale divisions to measure the signal amplitude, periodic time and frequency.
6. Change the signal amplitude and frequency and practice yourself to get the most accurate measurements using the oscilloscope.
7. Repeat the experiment to study signals of square and triangular waveforms.
8. Switch the horizontal control to X-Y and repeat the experiment. Can you see the signal waveform? Can you measure the signal amplitude and frequency?
9. Connect the signal to horizontal input. What are your comments? Can you improve horizontal amplifier sensitivity?

**Measuring signal drift:**

The average voltage of an AC signal is zero unless it is drifted to positive or negative side. The drift voltage is simply the DC average of any electronic signal. Most of signal generators have a drift control switch enables adding drift voltage of either positive or negative polarity. To measure the whole AC signal (including the drift) the channel input control must be set to DC coupling. If we are interested only to study the amplitude, frequency and waveform of the signal; AC coupling may give better sensitivity and resolution.

10. Add drift to the input signal and study the waveform on the screen in both DC and AC coupling modes.

**Studying two or more signals together:**

Most of oscilloscopes have more than one input channels. You have to choose to see one of the signals on the screen or all of them simultaneously. This enables you to compare more than one signal in the same time (for example the input and output of any electronic circuit).

11. Connect the second signal generator to CHB. Train/practice yourself to study one channel or both on the same screen.

**IV- Using X-Y mode to Compare frequencies of two signals (Lissajous figures)**

1. Set CHA control to AC coupling and sensitivity to 1.0V/cm.
2. Set horizontal control to X-Y mode.
3. Connect two sinusoidal signals of the same frequency one to CHA and the other to the horizontal input.
4- Fine tune one of the signal generators to see one loop on the screen. Is it a circle, ellipse, changing shape? Why?
5- Increase the frequency of the signal generator connected to CHA and notice the change in the trace specially at twice, three times, four times,… the frequency of the other signal generator.
6- Draw the waveforms of the trace obtained at these values.
7- Repeat steps 5-6 when you increase the frequency of the signal generator connected to horizontal channel.
8- The shapes of the trace obtained at \( n f_V = m f_h \) (n, m = 1, 2, 3, 4,…) are called Lissajous figures.

V- Measuring signals using PC-based oscilloscope (PCO)

1- Log into the computer and double click the Data Studio icon on your desktop to launch Data Studio Software.
2- Data Studio opens, a "Welcome to Data Studio" navigator screen will appear with four options Select Create Experiment from the startup screen.
3- Turn on the Science Workshop 750 Interface (on /off is at rear of interface).
4- Select “New Activity” from the File menu and choose 750 workshop interface.
5- The Sensors panel lists all possible sensors. Scroll through the list to find the voltage sensor and double-click the icon in the sensors panel.
6- The software will automatically choose the correct available port to connect the voltage sensor of CHA.
7- If you need to create a second channel (CHB); double click the voltage sensor again and connect another voltage sensor the interface.
8- To display the data choose oscilloscope display mode that plots a time-based graph rates. This display does not store data but shows a 'time-slice' snapshot of the data.
9- Repeat all possible experiments using PCO.
Millikan Experiment
Measuring the Charge of electrons

Objectives:
1- To study motion of charged particles in a viscous medium by observing the rising and falling of latex spheres (oil drops) in a vertical electric field.
2- To prove electric charge quantization.
3- To determine the charge of electron.

Introduction:
The charge to mass ratio \((e/m)\) of an electron is relatively easy to measure using electric and magnetic fields; however, to measure either the charge or mass separately is very difficult. The purpose of ‘Robert Millikan and Harvey Fletcher's oil-drop experiment’ (1909) was to measure the electric charge of the electron. The Millikan oil-drop experiment, recently ranked third of the top ten most beautiful experiments in the history of physics, maintains its significance and relevance into the twenty-first century.

Apparatus:
1- Cenco/Uchida model TM-15 Millikan apparatus. It contains:
   a) Drift chamber with two electrodes connected to variable high-voltage that produces a vertically controlled electric field.
   b) Electrode polarity switch
   c) Atomizer used to spray very small latex spheres in the chamber.
   d) A microscope with a focus adjusting knob to monitor the motion of the spheres.
   e) An incandescent lamp projector.
2- A ‘Pupil Cam’ CCD camera attached to the microscope.
3- Digital voltmeter.
4- Computer with Applied Vision Software.

The charge of an electron \((e)\) can be determined by two methods:
1- Studying the Statics of fixed oil drops:
The experiment is done by carefully balancing the gravitational and electric forces on tiny charged droplets of oil suspended between two metal electrodes. Knowing the electric field, the charge on the oil droplet could be determined. The electric field strength \( E \) is calculated by:

\[
E = \frac{V}{d}
\]

And weight of the oil-droplet is simply; \( W = mg = (\text{Vol. oil-density. g}) \) which is balanced by an electric force \( F = qE \).

\[
qE = q \frac{V}{d} = \frac{(4/3) \pi r^3 \rho_o g}{\rho_p} \quad (1)
\]

Where \( q \) is the charge of the oil drop/latex sphere (as the case may be), \( E \) is the electric field intensity, \( r \) is the radius of oil/latex-sphere, \( \rho_{o,p} \) is the density of particle (for latex \( \rho_p = 1050 \text{ Kg/m}^3 \)), \( V \) is the applied voltage across the plates, \( d \) is the separation distance between them. (In this apparatus \( d = 5 \times 10^{-3} \text{ m} \)).and \( g \) is the gravitational acceleration.

Repeating the experiment for many times, the values measured will always be multiples of the same number (\( q = ne \)) where \( n = 1, 2, 3, 4, \ldots \), and \( e \) is the charge on a single electron \( = 1.602 \times 10^{-19} \text{ Coulomb} \) (SI unit for electric charge). Balancing the force is a bit tricky, i.e. it is difficult to perceive that whether the particle is really static or drifting up/down at extremely low-speeds.

2- Studying the Dynamics of particles moving in a viscous medium:

If spherical drops are falling (or rising) at low velocities in a viscous fluid, the fluid drag on the drops can be calculated using Stoke’s Law:

\[
F = 6\pi \eta v_g
\]

where:
- \( F \) is the viscosity frictional force,
- \( r \) is the Stokes radius of the particle (for latex spheres \( r = 5.01 \times 10^{-7} \text{ m} \)),
- \( v_g \) is the particles speed falling with only gravity and viscous drag acting on it.
- \( \eta \) is the fluid (air) viscosity = \( 1.8479 \times 10^{-5} + 0.00275 \times 10^{-5} \text{ (T-72 deg F)} \)

The SI units of viscosity are Ns/m\(^2\), (Poise are cgs units of dyne s/cm\(^2\)).

For a calculator see:

Effective viscosity:

The value of \( \eta \) depends also on the radius of the moving sphere. The effective value is calculated as:

\[
\eta_{\text{effective}} = \eta \left(1 + \frac{b}{pr}\right)^{-1}
\]
Where \( b \) is a constant, \( b = 6.17 \times 10^{-6} \) m cm of Hg and \( p \) = barometric pressure in cm of Hg.

**Falling under gravitational force only (with no electric field):**

If the particles are falling in a viscous fluid (air) due to their own weight, because of their large area to mass ratio, they reach terminal velocity (steady velocity) very quickly. We can derive their settling velocity by equating this frictional force with the gravitational force – the buoyant force:

\[
F_g = \text{weight - buoyant force} = \text{Volume} \times \text{object density} \times g - \text{Volume} \times \text{fluid density} \times g
\]

\[
= \left(\frac{4}{3} \pi r^3\right) \rho_p g - \left(\frac{4}{3} \pi r^3\right) \rho_f g
\]

\[
v_g = \frac{2 r^2 g (\rho_p - \rho_f)}{9 \eta_{\text{effective}}}
\]

Where:

- \( \rho_p \) is the density of the particles; oil drops or latex spheres.
- \( \rho_f \) is the density of the fluid; air in this case.

**Note:** Electrostatic force acting on negatively charged particles is opposite in direction to that of the electric field.

**Rising under the effect of a downward electric field:**

Turn on a downward electric field to produce an upward force on the “oil drop” or latex sphere. Again, the drop very quickly reaches a constant upward velocity \( v^+ \).

\[
\text{Forces upward} = \text{Forces downward}
\]

\[
\text{Electrical Force + Buoyant Force} = \text{Weight + Frictional Force}
\]

\[
qE + (\text{Volume} \times \text{fluid density} \times g) = mg + 6\pi r \eta_{\text{effective}} v^+
\]

Where: \( v^+ \) is the upward velocity of the oil drop.

**Falling under the effect of an upward electric field:**

Now turn on an upward electric field of the same intensity to produce a downward force on the “oil drop”. The drop very quickly reaches a constant upward velocity \( v^- \).

\[
\text{Forces upward} = \text{Forces downward}
\]

\[
\text{Frictional Force + Buoyant Force} = \text{Weight + Electrical Force}
\]

\[
6\pi r \eta_{\text{effective}} v^- + (\text{Volume} \times \text{fluid density} \times g) = mg + qE
\]

Subtracting Equation “downward” from Equation “upward” gives:

\[
|g| = \frac{6\pi r \eta_{\text{effective}} (v^+ + v^-)}{2E}
\]

(2)
Digital Video Microscopy:

We employ a digital CCD camera attached, through a Applied Vision software to trace the motion of the Latex spheres as they rise or fall under the influence of applied electric field and gravity. This software allows us to capture a (nearly) real time image of what happen inside the drift chamber. Moreover we have the option to edit and store a set of successive frames with predefined periodic time. This helps to review the frames one by one and to study the motion of more than one particle at a time.

Preparations of the experimental set-up:

1- Connect the CCD camera to the computer, run the Applied Vision software, switch on the projector lamp and check that you can see a clear frame on the screen.
2- The microscope must be focused at the center of the drift volume. To focus the microscope hold a piece of wire at the center of the drift volume and move the light and microscope until you can see a bright, sharp image of the wire with a dark background.
1- Use Alcohol to clean the drift chamber and atomizer then leave it to dry before starting the experiment.
2- Calibrate the microscope scale; Check that the interior scale of the microscope is reading accurately. Then put a small external scale (perhaps from ‘Vernier calipers’) at the focus of the microscope and use the built in interior scale to read the external scale. The scales probably won’t agree so adjust your readings to compensate for the optical distortion.
3- Use a Vernier caliper to check the separation distance between the plates, this is a small distance and any errors can lead to large percent errors.

Experimental Procedure:

First: Using Static method:

1- Prepare the experiment.
2- Turn on the voltage, 300V perhaps and the polarity switch up (downward E).
3- Slightly loosen the plates so air can escape.  
   Put your finger over the hole in the aspirator and give a small puff of air and “oil drops/latex” and wait for some drops/spheres to appear.
4- Monitor the oil drops/spheres on the screen.
5- Readjust the voltage to bring one or more oil drops to stop (balance) then read the voltage V.
6- Use equation (1) to determine the value of q.
7- Repeat many times as possible and determine the charge of each oil drop then go to data analysis to calculate e.

**Second: Using Dynamic method:**
1- Prepare the experiment.
2- Turn on the voltage, 300V perhaps and the polarity switch up (Downward E).
3- Slightly loosen the plates so air can escape.
4- Prepare the software to store a set of successive frames (5 fr/sec is a suitable rate).
   Put your finger over the hole in the aspirator and give a small puff of air and “oil drops/latex spheres” and wait for some drops to appear on the screen.
5- Readjust the voltage to bring one or more oil drops to rise slowly. Then start the computer to capture frames.
6- After few seconds, with the voltage unchanged, reverse the polarity switch to inverse the field direction and the drops fall down very fast.
7- After another couple of seconds stop the frame capture process.
8- Study the stored successive frames to acquire position and time data (in meters and seconds) for one (or more).
9- Plot the position time graphs for each particle while it is moving up and down.
10- The slope of the two graphs gives \( v^+ \) and \( v^- \), respectively.
11- Use equation (2) to determine the value of q. Repeat for many particles as possible then go to data analysis to calculate the electron charge as done before.

**Data Analysis:**

Electric charge is quantized; which means \( q = n e \), where \( n \) is an integer. Practically don’t expect integers greater than ten so. To calculate the experimental value of e; follow the following steps:

1- Find the charge for each “oil drop/ latex sphere”.
2- Make a histogram of charge verses number of occurrences of that charge.
3- Find the maximum electron charge that will go into all your charges an integer number of times.
4- Find the usual average, standard deviation of the mean, percent error, error sources, etc.
Determining Planck’s constant
Using
Light Emitting Diodes (LED’S)

I. Introduction:
Modern physics incorporates the viewpoint that bound systems (atoms, molecules, particles-in-boxes, harmonic oscillators etc.) can exchange (gain or lose) energy only in discreet amounts, or quanta. Planck’s constant $\hbar$ is one of the fundamental constants of nature, having to do with the amount of energy in one quantum. For example it is understood that electromagnetic radiation, including visible light, is emitted and absorbed by physical systems only in discreet amounts. A quantum of light is called a photon and possesses energy $E = hf$ (and momentum $p = hf/c$) where $f$ is the frequency of the electromagnetic wave and $c$ is the free-space speed of light.

To determine Planck’s constant experimentally, it is necessary to measure the energy of a photon of known frequency. There are two ways to make this measurement. One can either look at the energy gained by a material when it is struck by a photon and absorbs its energy or one can look at the energy lost by the system when the photon is produced. The photoelectric effect experiment falls into the first category. When light strikes metal surfaces, electrons are emitted from the surface. But in this experiment, one can determine Planck’s constant by measuring the energy ($E$) lost by a system (LED) upon emitting a photon of light of frequency $f$, using the expression $E = hf$.

Light Emitting diodes LEDs:

LEDs are special semiconductor diodes that emit light when biased forward (current is injected). The most important part of a (LED) is the semi-conductor chip located in the center of the bulb as shown at the right. The chip is simply a P-N junction formed of special semiconductor materials. A clear (or often colored) epoxy case enclosed the heart of an LED, the semi-conductor chip.
**Light emission and color of LED:**

When sufficient voltage is applied to the chip across the ‘leads’ of the LED, electrons can move easily in only one direction across the junction between the $P$ and $N$ regions. In the $P$ region there are many more positive than negative charges. In the $N$ region the electrons are more numerous than the positive electric charges. When the current starts to flow, electrons in the $N$ region have sufficient energy to move across the junction into the $P$ region. Once in the $P$ region the electrons are immediately attracted to the positive charges due to the mutual Coulomb forces of attraction between opposite electric charges. When an electron moves sufficiently close to a positive charge in the $P$ region, the two charges "recombine". Each time an electron recombines with a positive charge; electric potential energy is converted into electromagnetic energy. For each recombination an electromagnetic energy is emitted in the form of a photon of light with a frequency characteristic of the semi-conductor material (usually a combination of the chemical elements gallium, arsenic and phosphorus), this is called **radiative recombination** mechanism. Only photons in a very narrow frequency range (nearly one color) can be emitted by a given material. LED's that emit different colors are made of different semi-conductor materials, and require different energies to light them.

The electric energy needed to switch on a LED is $E = eV_{\text{turn-on}}$ [Joules], where $e$ is the electric charge of an electron ($e = -1.6 \times 10^{-19}$ Coulomb) and $V_{\text{turn-on}}$ is the voltage required to overcome the barrier created by $pn$-junction. This energy is different for different LED color (frequency of emitted light, $f$). Each electron-hole radiative recombination emits a light photon of energy $E = hf = h(c/\lambda)$ where $c$ is the speed of light ($3 \times 10^8$ m/s) and $\lambda$ is the wavelength of light.

**Relation of bandgap energy to turn-on voltage:**

A LED is a particular example of a variety of semiconductor $pn$- junction that conducts electric current only in the forward bias direction, and will not conduct if the applied voltage is reversed.

To understand how a $pn$- junction diode works, begin by imagining two separate bits of semiconductor, one N-type, the other P-type. Bring them together and join them to make one piece of semiconductor which is doped differently either side of the junction. Free electrons on the $N$-side and free holes on the $P$-side can initially wander across the junction. When a free electron meets a free hole it can 'drop into it'. So far as charge movements are concerned this means the hole and electron cancel each other and vanish. As a result, the free electrons near the junction tend to eat each other, producing a region depleted of any moving charges. This creates what is called the **depletion zone**. Now, any free charge which wanders into the depletion zone finds itself in a region with no other free charges. Locally it sees a lot of positive charges (the donor atoms) on the n-type side and a lot of negative charges (the acceptor atoms) on the p-type side. These exert a force on the free charge, driving it back to its 'own side' of the junction away from the depletion zone. The acceptor and donor atoms are 'nailed down' in the solid and cannot move around. However, the negative charge of the acceptor's extra electron and the positive charge of the donor's extra proton (exposed by its missing electron) tend to keep the depletion zone swept clean of free charges once the zone has formed. A free charge
now requires some extra energy to overcome the forces from the donor/acceptor atoms to be able to cross the zone. The junction therefore acts like a barrier, blocking any charge flow (current) across the barrier. Usually, we represent this barrier by 'bending' the conduction and valence bands as they cross the depletion zone. Now we can imagine the electrons having to 'get uphill' to move from the $N$-type side to the $P$-type side. The holes behave a bit like balloons bobbing up against a ceiling. On this kind of diagram you require energy to 'pull them down' before they can move from the $P$-type side to the $N$-type side. The energy required by the free holes and electrons can be supplied by a suitable voltage applied between the two ends of the $pn$-junction diode.

This action is usually described using a conventional ‘energy level diagram’ of the sort shown in figure (1). The electrons can roll around the ‘flat’ parts of the energy diagram, but need extra energy to roll up the step and move from N-type to P-type across the junction. Coming the other way they’d ‘drop down’ and zip into the N-type material with extra kinetic energy. The size of this energy barrier can be defined in terms of a junction voltage $V_d$. This means the amount of energy converted from kinetic to potential form (or vice versa) when an electron crosses the depletion zone is $eV_d$ where $e$ is the charge on a single electron.

![Figure (1) – Unbiased P-N junction](image)

The electrical properties of the diode can now be understood as consequences of the formation of this energy barrier & depletion zone around the $pn$-junction. The first thing to note is that the depletion zone is free of charge carriers & the electrons/holes find it difficult to cross this zone. As a result, we can expect very little current to flow when we apply a small potential difference. (Here, ‘small’ mean small compared with $V_d$, which an electron requires to get over the potential barrier). Notice that this voltage must be supplied the correct way around, this pushes the charges over the barrier.

**Biased $pn$-junction:**

A junction is biased forward if the $P$-side is connected to the positive terminal of an external voltage supply and the $N$-side is connected to the negative terminal. We force lots of extra electrons and holes into junction region. Electrons near the junction are helped across the junction by being shoved from behind. The effect is to reduce the amount of extra energy required to cross the barrier — i.e. the barrier height reduces. As a result, the barrier is reduced or removed and free electrons/holes can move freely from one material to the other. Energy level diagram’ of forward bias is shown in figure (2-a).
When forward biased, the diode conducts a large current if the applied voltage is above the “turn-on” voltage, \( V_{\text{turn-on}} = V_d \) and the current thereafter rises very rapidly with increasing applied voltage. Below the turn-on voltage, it conducts very little current and emits no light. Above the turn-on voltage, the LED emits light via transitions that are taking place between energy levels pertaining to the whole of the solid material. This is a distinctly different process from the more usual situation in which light is emitted as the result of transitions between the energy levels of individual atoms.

Figure (2)

(a) Forward bias  
(b) reverse bias

If the \( P \)-side is connected to the negative terminal of the external voltage supply and the \( N \)-side is connected to the positive terminal the \( pn \)-junction is reverse biased. The effect is to pull free charges away from the junction, increase the amount of extra energy required to cross the barrier (the barrier height increases) and as a result, there will be no current flow because of majority carriers but a negligible, very small amount of, current because of minority carriers crossing the junction. Energy level diagram’ is shown in figure (2-b).

In summary, the most important point to remember about the \( P-N \) junction diode is its ability to offer very little resistance to current flow in the forward-bias direction but maximum resistance to current flow when reverse biased. Figure 3 shows a plot of this voltage-current relationship (characteristic curve) for a typical \( pn \)-junction diode.
References:

You should be familiar with semiconductors and the semiconductor diode (p-n junction diode) at the level of a general physics text. For example,
1- Fundamentals of Physics by Halliday and Resnick.

Experimental Work:

Review for the experiment:

An LED requires a certain minimum forward-bias voltage before it will light up. As explained later, this “turn on” voltage is related to the band-gap energy $V_d$:

$$V_d = eV_{\text{turn-on}} + \Delta E$$

(1)

Where $\Delta E$ is constant which is different from one LED to another.

Note that, if $e$ is the electronic charge, then $eV_{\text{turn-on}}$, represents the energy received from the power supply by each electron crossing the junction. Since the band-gap energy will be the energy carried away by a photon, then:

$$V_d = E_{\text{photon}} = hf,$$

Eq. (1) becomes

$$hf = eV_{\text{turn-on}} + \Delta E$$

(2)

In this experiment we use Eq. (2) to determine Planck’s constant $h$. We use several LED’s that emit light of different colors (frequencies). We measure the turn-on voltage for each, and make a graph of light frequency “f” as a vertical axis against the turn-on voltage “$V_{\text{turn-on}}$”. According to Eq. (2), the slope of the graph is $(h/e)$ where $h$ is Planck’s constant.

Apparatus:

1- Neva 678903 LED apparatus (distributed by TEL-Atomic incorporated) shown in figure (4), contains:
   A) 6 LED’s of different wavelengths.
   B) Connection terminals.
   C) $R=100$ Ohm limiting resistance.

2- 0-12 V DC power supply.

3- Two digital Voltmeters.

Figure (4)
The characteristics of the 6 LED’s is given in the following data:

<table>
<thead>
<tr>
<th>LED Color</th>
<th>Wavelength [nm]</th>
<th>Max. current [mA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infra Red</td>
<td>950</td>
<td>100</td>
</tr>
<tr>
<td>Red</td>
<td>665</td>
<td>50</td>
</tr>
<tr>
<td>Super Red</td>
<td>635</td>
<td>50</td>
</tr>
<tr>
<td>Green</td>
<td>590</td>
<td>50</td>
</tr>
<tr>
<td>Yellow</td>
<td>560</td>
<td>50</td>
</tr>
<tr>
<td>Blue</td>
<td>480</td>
<td>20</td>
</tr>
</tbody>
</table>

**Procedure:**

PROCEDURE

1. Connect an LED according to the circuit below. The series resistor (100 Ω) is necessary to limit the current through the diode. It is also used to measure the current passing through the LED.

\[ I = \frac{V_R}{100} \]
2. Record the frequency \( f = \frac{c}{\lambda} \) and the maximum current of the diode that was provided by the manufacturer.

3. Slowly increase the forward bias voltage until the diode lights up, with moderate brightness. For each point record the diode voltage and the corresponding diode current. **Do not exceed the maximum diode current.**

4. Use computer software to plot a graph of \( I \) (vertical axis) against \( V \) (horizontal axis). Draw a tangent to the curve to intersect the horizontal axis at \( V = V_d \).

5. Repeat procedure 2-5 for all of the 6 diodes.

6. Make a graph of diode light frequency \( f \) (vertical) against \( V_d \) (horizontal). Use computer software to determine the slope of the best straight line fits the data points.

7. Determine Planck’s constant \( h = \text{(slope)} \times e \)

8. Compare the value of Planck’s constant with the standard value and compute the percent error in your experiment.

**Note:** If directed by the instructor, measure the wavelength of light that is emitted by each diode, using a grating spectrometer.
Exp. # (4)

Photo-electric Effect and Measurement of $h/e$

Objectives:

1- To study the photo-electric emission of electrons from a metal surface.
2- To experimentally determine the value of Planck's constant "$h" by making use of the spectral dependency of the photoelectric effect.

Introduction:

In late 19th century, Max Planck was working on a theory of black body radiation, and ran into quantum theory of radiation. It states that oscillators responsible for absorption and emission of light have discrete spectra of energy, and that the values in between are forbidden. The smallest unit of light that can be emitted or absorbed is called a photon. The photon energy $E$ is called light quantum which equals:

$$E = h \nu = h f$$

Where:

$\nu$ is the frequency of radiation and $h$ is a fundamental constant. The constant, later known as Planck's constant, has significance beyond the model of black body radiation, and is a major building block of Quantum Mechanics and Quantum Field Theory.

Einstein’s model for photoelectric emission:

Photoelectric emission is a process in which light strikes a surface of material (e.g. a metal), and electrons are ejected. The kinetic energy of these electrons can be measured by subjecting them to a retarding potential. The maximal kinetic energy is obtained when the electric field is strong enough to overcome all electrons i.e. the opposing field is strong enough so that all the electrons reaching the collecting electrodes are blocked. In early 1900s, several experiments showed that:

1- The kinetic energy of electrons depended on the color of the light (i.e., its frequency) and not on its intensity, and that dependence is linear. There exists a threshold frequency (some minimal frequency) below which the light is unable to free any electrons, whereas above that critical frequency the light always succeeds in liberating electrons no matter how week the intensity may be.
2- The photoelectric current (the number of electrons emitted) depended on intensity of the light.

These experimental facts ran counter to the classical intuition of the time, since in the classical model the intensity of the light would imply larger amplitude of the light waves, which would result in larger energy transfer to electrons when the light hit the atoms of the surface.
Einstein took Planck's theory one step further and in 1905 stated that in the photoelectric process a photon of energy \( E = h \nu \) is absorbed by electrons that are assumed to be bound within the surface of material with some energy. The minimum value of bound energy is called the work function \( (W_o) \) and is a property of the material. The energy of the photon is used by the electron to escape the material surface and the rest is electron's kinetic energy \((KE)\). The maximum kinetic energy of the emitted (escaped) electron is given by Einstein's famous equation:

\[
KE_{\text{max}} = h\nu - W_o
\]

If a retarding (stopping) potential \( V \) is used to stop electrons, that will happen when \( eV = KE_{\text{max}} \). When solved for stopping potential \( V \), this turns into

\[
V = \left(\frac{h}{e}\right)\nu - \left(\frac{W_o}{e}\right)
\]

If we plot \( V \) vs. \( \nu \) for different frequencies of light, the graph will look like Figure (1). 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 \( e=1.602 \times 10^{-19} \) coulombs, we can determine Planck's constant, \( h \).

**Note:** Max Planck was awarded the Nobel Prize in 1918 for his quantum theory and Albert Einstein got his in 1921 - for the explanation of the photoelectric effect.

**Apparatus:**
1- PASCO Scientific OS-9286 Mercury Vapor Light Source. The most readily available lines are:

<table>
<thead>
<tr>
<th>Color</th>
<th>Frequency ([10^{14} \text{ Hz}])</th>
<th>Wavelength ([\text{nm}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yellow</td>
<td>5.18672</td>
<td>578</td>
</tr>
<tr>
<td>Green</td>
<td>5.48996</td>
<td>546.074</td>
</tr>
<tr>
<td>Blue-green (weak)</td>
<td>6.09830</td>
<td>491.6</td>
</tr>
<tr>
<td>Blue</td>
<td>6.87858</td>
<td>435.835</td>
</tr>
<tr>
<td>Violet</td>
<td>7.40858</td>
<td>404.656</td>
</tr>
<tr>
<td>Ultraviolet</td>
<td>8.20264</td>
<td>365.483</td>
</tr>
</tbody>
</table>

- The values for green, blue, violet and ultraviolet are copied from PASCO manual.
- Ultraviolet light can be seen on the white reflective mask of the h/e apparatus, which is made of a special fluorescent material. Ultraviolet line will appear as blue. The violet will also appear bluish.

2- Pasco scientific h/e head AP-9368.
3- Optic and alignment kit AP-9369.
4- Digital voltmeter.
5- Pasco instruction manual with experimental guide. You can get it at: https://wiki.brown.edu/confluence/download/attachments/29111/Pasco+Manual.pdf?version=1

**Experimental configuration and practical problems:**

Experimentally, we need a clean surface of a metal which will be exposed to light and yield electrons, and therefore called cathode below. We also need another surface to collect electrons - an anode - facing the cathode, and both are sealed in vacuum as shown in figure (2). We shine light of different intensities and frequencies (colors) onto the cathode, and it emits electrons that are collected on the anode. (The stream of electrons forms so-called photoelectric current.)

![Figure (2)]

**1- Using the filters**

The h/e apparatus (PASCO AP-9368) includes three filters:
- Green filter.
- Yellow filter
- Variable transmission filter:

All three have frames with magnetic strips and mount on the outside of the white reflective mask of the h/e apparatus.

Green and Yellow filter block the higher frequencies, which prevents the ambient room light from interfering with the lower frequency green and yellow lines from the mercury spectrum. These filters must be used when working with green and yellow spectral lines. They make the light “monochromatic” by eliminating the other colors.

The variable transmission filter (neutral density filter) does not affect the frequency of the incident light, but only its intensity. There are five slots for the input light with transmission percentages of 100%, 80%, 60%, 40% and 20% respectively. (As an aside, this filter actually consists of fine patterns of dots and lines generated by a computer.
2- Measuring stopping voltage:
In experiments with the \( h/e \) Apparatus, monochromatic light falls on the cathode plate of a vacuum photodiode tube that has a low work function, \( W_o \). Photoelectrons ejected from the cathode are collected on the anode. The photodiode tube and its associated electronics have a small capacitance which becomes charged by the photoelectric current. When the potential on this capacitance reaches the stopping potential of the photoelectrons, the current decreases to zero, and the anode-to-cathode voltage stabilizes. This final voltage between the anode and cathode is therefore the stopping potential of the photoelectrons.

Experimentally, the most challenging part is to have a precise measurement of the stopping voltage. The measurement of voltage was usually turned into the measurement of a very small current running through a high-resistance circuit.

a. classical approach:
This approach introduces a couple of difficulties, the most important being that now the anode and the cathode are coupled through an external circuit, and one must also take into account the `contact potential difference', which is in fact equal to the difference of work functions between the cathode and the anode! Thus the work function of the anode is dragged into the calculation and has to be measured separately.

b. Using PASCO AP-9368 apparatus:
The PASCO setup uses the photoelectric current itself to charge the anode and create the retarding potential! The photoelectric current will stop when the stopping potential is reached, and at that time the voltage between the anode and the cathode will equal the stopping voltage, \( V \). All this is possible if the measurement of \( V \) does not leak any charge from the anode.

To let you measure the stopping potential using PASCO AP-9368 apparatus the anode is connected to a built-in amplifier with an ultrahigh input impedance (> \( 10^{13} \) \( \Omega \)), and the output from this amplifier is connected to the output jacks on the front panel of the apparatus. This high impedance, unity gain (\( V_{out}/V_{in} = 1 \)) amplifier lets you measure the stopping potential with a digital voltmeter. Due to the ultra high input impedance, once the capacitor has been charged from the photodiode current it takes a long time to discharge this potential through some leakage.

This approach circumvents the problems present in the `classical' setup of the photoelectric experiment. However, it has two operational consequences:

- After the measurement, the anode has to be drained. This is achieved by a shorting circuit which is activated by pressing the button labeled "PUSH TO ZERO", which will quickly drain the charge. The anode voltage will reach zero, however the output of the built-in amplifier will float and therefore the output voltage will fluctuate, or even oscillate. This is perfectly normal. When the anode is charged again (in the next measurement), the voltage will stabilize.

- It may take some time to reach the stopping voltage. This is especially important when performing measurements with different intensities of input light. As a rule of thumb, one needs to add an extra minute of accumulation per each 20%-decrease of the input light intensity.
Note: Study the instruction manual carefully before starting the experiments:

**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 is 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 is 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.

**Setup**

Set up the equipment as shown in figure (3).

- 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.

![Figure (3)](image)

- 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.

- 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.

Procedure

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

<table>
<thead>
<tr>
<th>Color # 1 Name:</th>
<th>% transmission</th>
<th>Stopping voltage</th>
<th>Approximate charge time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>80</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>60</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>20</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Color # 2 Name:</th>
<th>% transmission</th>
<th>Stopping voltage</th>
<th>Approximate charge time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>80</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>60</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>20</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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.
Analysis
1. Describe the effect that passing different amounts of the same colored light through a 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.
2. Describe the effect that different colors of light had on the stopping potential and thus the maximum energy of the photoelectrons.
3. Defend whether this experiment supports a wave or a quantum model of light based on your lab results.
4. Explain why there is a slight drop in the measured stopping potential as the light intensity is decreased.

NOTE: While the impedance of the zero gain amplifier is very high (>10^{13} \, \Omega), it 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.

<table>
<thead>
<tr>
<th>Light Color</th>
<th>Stopping Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yellow</td>
<td></td>
</tr>
<tr>
<td>Green</td>
<td></td>
</tr>
<tr>
<td>Blue</td>
<td></td>
</tr>
<tr>
<td>Violet</td>
<td></td>
</tr>
<tr>
<td>Ultraviolet</td>
<td></td>
</tr>
</tbody>
</table>

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.

Setup
1- Set up the equipment as shown in the figure (3).
2- Focus the light from the Mercury Vapor Light Source onto the slot in the white reflective mask on the h/e Apparatus.
3- Tilt the Light Shield of the Apparatus out of the way to reveal the white photodiode mask inside the Apparatus.
4- 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.
5- 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 bands.
6- Return the Light Shield to its closed position.
7- 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.
Procedure
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.

Analysis
Determine the wavelength and frequency of each spectral line. Plot a graph of the stopping potential vs. frequency.
Determine the slope and y-intercept. Interpret the results in terms of the $h/e$ ratio and the $WO/e$ ratio. Calculate $h$ and $WO$.
In your discussion, report your values and discuss your results with an interpretation based on a quantum model for light.

<table>
<thead>
<tr>
<th>First order Color</th>
<th>Wavelength [nm]</th>
<th>Frequency $\times 10^{14}$Hz</th>
<th>Stopping voltage [Volts]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yellow</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Green</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blue</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Violet</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ultraviolet</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Second order Color</th>
<th>Wavelength [nm]</th>
<th>Frequency $\times 10^{14}$Hz</th>
<th>Stopping voltage [Volts]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yellow</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Green</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blue</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Violet</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ultraviolet</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Experiment # (5)  
Franck-Hertz Experiment

Introduction and Background:

Bound systems, such as atoms and molecules, possess stationary states. That is, the total energy of the atom or molecule is quantized, with one possible value of the total energy corresponding to each of the allowed states. When the atom or molecule is in a stationary state, its total energy is constant. In a stationary state, the atom neither absorbs nor radiates energy. The energies corresponding to the stationary states are called the energy levels of the system. An atom or molecule can undergo a transition from one stationary state to another of higher energy only by absorbing exactly the correct amount of energy from an external source; similarly, if a transition occurs from one state to another of lower energy, the energy difference must be emitted to the surrounding. The first experimental evidence for this was obtained in an experiment by Franck and Hertz in 1914, for which they received the Nobel Prize for physics in 1926. The following discussion is taken from the book Fundamental University Physics by Alonso and Finn:

Experimental Evidence of Stationary States:

So far we have introduced the idea of stationary states as a convenient concept to explain the discrete spectrum of atomic systems. However, the existence of transitions between stationary states is amply corroborated by many experiments. The most characteristic is that of inelastic collisions, in which part of the kinetic energy of the projectile is transferred as internal energy to the target. These are called inelastic collisions of the first kind. Inelastic collisions of the second kind correspond to the reverse process.

Suppose that a fast particle \( q \) collides with another system \( A \) (which may be an atom, molecule, or nucleus) in its ground state of energy \( E_1 \). As a result of the projectile-system interaction (which may be electromagnetic or nuclear) there is an exchange if energy. Let \( E_2 \) be the energy if the first excited state of the system. The collision will be elastic (i.e., the kinetic energy will be conserved) unless the projectile has enough kinetic energy to transfer the excitation energy \( E_2 - E_1 \) to the target. When this happens the collision is inelastic, and we may express it by:

\[
A + q_{\text{fast}} \rightarrow A^* + q_{\text{slow}}
\]

When the mass of the projectile \( q \) is very small compared with that of the target \( A \), as happens for the case of an electron colliding with an atom, the condition for inelastic collision is:

\[
E_k \geq E_2 - E_1
\]

Where \( E_k = \frac{1}{2} mv^2 \) is the kinetic energy of the projectile before the collision. The kinetic energy of the projectile after the collision is then \( E'_k = E_k - (E_2 - E_1) \), since the energy lost by the projectile in the collision is \( E_2 - E_1 \).
To give a concrete example, suppose that an electron of kinetic energy $E_k$ moves through a substance, let us say mercury vapor; as shown in figure (1). Provided that $E_k$ is smaller than the first excitation energy of mercury, $E_2 - E_1$, the collisions are all elastic and the electron moves through the vapor, losing energy very slowly, since the maximum kinetic energy lost in each collision is approximately:

$$\Delta E_k \approx -4\left(\frac{m_e}{M}\right)E_k \approx 5 \times 10^{-6} E_k$$

However, if $E$ is larger than $E_2 - E_1$, the collision may be inelastic and the electron may lose the energy $E_2 - E_1$ in a single encounter. If the initial kinetic energy of the electron was not much larger than $E_2 - E_1$, the energy of the electron after the inelastic collision is insufficient to excite other atoms. Thereafter the successive collisions of the electron will be elastic. But if the kinetic energy of the electron was initially very large, it may still suffer a few more inelastic collisions, losing the energy $E_2 - E_1$ at each collision and producing more excited atoms before being slowed down below the threshold for inelastic collisions.

This process was observed for the first time in 1914 by Franck and Hertz using a set up as shown in figure (2). A metal oxide coated heated cathode $C$ emits electrons which are accelerated toward the grid (Perforated anode) by a variable Potential $V$. The space between $C$ and $G$ is filled with mercury vapor. Between the grid and the collecting plate $P$ a small retarding potential $V_r$, of approximately -1.5 volt, is applied so that those electrons which are left with very little kinetic energy after one or more inelastic collisions cannot reach the plate and are not registered by the galvanometer. A current of the order of $10^{-10}$ A flows from the collector electrode to the anode and is indicated with the measuring amplifier.

Figure (1) Excitation of a Hg atom.

Figure (2) Franck-Hertz experiment Tube
As V is increased, the plate current I fluctuates as shown in Figure (3), the peaks occurring at a spacing of about 4.9 volts. The first dip corresponds to electrons that lose all their kinetic energy after one inelastic collision with a mercury atom, which is then left in an excited state. The second dip corresponds to those electrons that suffered two inelastic collisions with two mercury atoms, losing all their kinetic energy, and so on. The excited mercury atoms return to their ground state by emission of a photon, according to \( Hg^* \rightarrow Hg + h\nu \) with \( h\nu = E_2 - E_1 \). From spectroscopic evidence we know that mercury vapor, when excited, emits radiation whose wavelength is \( 2.536 \times 10^{-7} \text{ m} \) (or \( 2536 \text{ Å} \)), corresponding to a photon of energy \( h\nu \) equal to 4.86 eV. Radiation of this wavelength is observed coming from the mercury vapor during the passage of the electron beam through the vapor. Thus this simple experiment is one of the most striking proofs of the existence of stationary states.

\[ \text{Figure (3) I-V curve for Hg.} \]

The current minima are spaced at intervals of 4.9 V in the average, showing that the excitation energy of the mercury atoms is 4.9 eV. The spectral frequency corresponding to this energy is:

\[ \nu = \frac{E}{h} = \frac{4.9V}{4.133 \times 10^{-15} \text{ eVs}} = 1.18 \times 10^{15} \text{ Hz} \]

And the corresponding wavelength is

\[ \lambda = \frac{c}{\nu} = 253.7 \text{ nm}. \]

Franck and Hertz verified the presence of this ultraviolet radiation with the aid of a quartz spectrograph.
**Note:** A contact potential of about 2 V exists between the cathode and the anode of the tube, so that the first current minimum is found for an applied accelerating voltage of about 7 V.

**Apparatus:**

1- KA6040 Franck-Hertz tube, mercury filled.

**Description of the tube:**

a. A three electrode tube with an indirectly heated oxide coated cathode, grid anode, and collector electrode.

b. Electrons are emitted thermo-ionic-ally from an indirectly heated cathode, secondary and reflected electrons are eliminated by a metal diaphragm connected to the cathode.

c. To avoid deformation of the electric field the tube uses a planoparallel system of electrodes.

d. Design of this Klinger tube is similar to that originally used by Franck and Hertz to directly measure excitation potentials. This design provides for rigid mounting and stable positioning of the electrodes which insures dependable results. In order to maintain the proper operating temperature, the tube is housed in a thermostatically controlled metal oven.

e. The distance between the cathode and the grid (perforated anode) is large compared with the mean free path length in the mercury vapor atmosphere in order to ensure a high collision probability. The separation between the anode and the collector electrode is relatively small.

f. Leakage current along the hot gloss wall of the tube is minimized by use of a ceramic feed—through on the plate (counter electrode).

g. The tube is highly evacuated and contains a measured quantity of purified metallic mercury. When raised to its proper operating temperature (at 180 deg.) the mercury within the tube is in vapor state, thus providing a suitable atmosphere for the measurement of excitation potentials of mercury.

h. During manufacture, the tube is provided with a highly activated contact getter and exhausted to high vacuum. The getter is effective for a long time, so that no deterioration of the characteristics through energy-consuming molecular gases takes place when operating the tube.

<table>
<thead>
<tr>
<th>Specifications</th>
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<tbody>
<tr>
<td>Tube</td>
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<tr>
<td>Heater</td>
</tr>
<tr>
<td>Grid voltage</td>
</tr>
<tr>
<td>Operating temperature</td>
</tr>
<tr>
<td>Counter-voltage</td>
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</table>

The Franck-Hertz-tube is mounted on the rear side of the front panel in such a manner that the entire tube including the connecting wires is heated to a constant temperature. This is absolutely essential, because the vapor pressure of the mercury is always determined by the temperature of the coldest point of the tube.
2- KA6041 Franck-Hertz Oven, (Hg) Heating oven:
A steel cabinet, heated by a solid element and the temperature is controlled by a thermostat located on the side. The front panel carries ceramic insulated connecting sockets for the tube. The collector electrode is connected to a BNC jack for connection to the F-H operating unit. The symbolic designation of the tube is marked on the front panel in bold lines, while the circuit is delineated in thinner lines. The oven possesses two glass windows through which the tube and heating element can be viewed. The cover plate accommodates a thermometer for monitoring the temperature.

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<th>Specifications</th>
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<tbody>
<tr>
<td>Heater</td>
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<tr>
<td>Temperature range</td>
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<tr>
<td>Constant temperature precision</td>
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<tr>
<td>Dimensions</td>
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<tr>
<td>Weight</td>
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</table>

1- Operating Unit for Franck-Hertz-Experiment No. 6756. This unit provides all voltages necessary for either Hg tube and also contains a highly sensitive DC amplifier for measuring the collector current. Set up of the Franck-Hertz experiments becomes quite simple when using this unit. A saw-tooth waveform accelerating voltage can be produced when the experiment is run with an oscilloscope. When set to maximum sensitivity, a collector current of 5 x 10^{-11} A produces a signal output of 1 V. The collector current is amplified so that signal voltages up to 10 V are available for vertical deflection.

<table>
<thead>
<tr>
<th>Specifications</th>
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<tbody>
<tr>
<td>Filament voltage</td>
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<tr>
<td>Control voltage</td>
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<tr>
<td>Accelerating voltage</td>
</tr>
<tr>
<td>Operating modes</td>
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<tr>
<td>Counter-voltage</td>
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**Analog outputs:**

<table>
<thead>
<tr>
<th>Signal output</th>
<th>0 – 12 V @ 7 nA/V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerating voltage</td>
<td>UA/10 for oscilloscope</td>
</tr>
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</table>

**The operating unit can be alternatively replaced by the following equipment:**
1- A 6.3 V DC or AC voltage source (Cathode heating voltage).
2- Dc Power supply 0 to +80 V (Anode voltage).
3- Digital Pico-ammeter or Electrometer.
4- A DC power supply 1.5 V (Stopping voltage).
5- A thermometer reading up to 200° C.
6- A voltmeter with 3 V DC and 100 V DC measuring ranges.
Experimental Procedure:

1- Connect the heating oven to a grounded AC mains power point with the aid of the provided mains cable. Set the bimetal contact switch to the desired temperature. The temperature can be read on the thermometer inserted to the oven. This temperature will be reached after a warm-up time of 10 to 15 minutes (e.g. 180°C). The temperature set in this manner is automatically held constant.
2- Establish the connections to the operating unit to the voltage sources and to the measuring devices according to the markings on the front panel. A shielded cable must be used for the connection from the collector electrode to the electrometer.

3- Make sure that the polarities of the accelerating voltage and opposing voltage are correct. The negative pole of the accelerating voltage must be connected to the cathode socket K (bottom right). If you are using separate voltage sources (accelerating voltage, cathode heating voltage and opposing voltage) they must be floating to ground.(no galvanic connection to ground or chassis), because the apparatus is already grounded via the measuring electrometer.

4- The indirectly heated cathode requires a warm-up time of about 90 seconds after applying the heater voltage.

5- The polarity of the collector electrode is negative with respect to the anode. Correct corresponding polarity must be observed for the meter connected to the output of the measuring electrometer.

6- The emission current in the tube and thus the collector electrode current are affected by the cathode temperature. If the current is too small the cathode heater voltage may be increased (e.g. to 8 V). The heater current must then be adjusted with a rheostat or rotary potentiometer control such that the collector electrode current is of the order $10^{-10}$ A with 50 V accelerating voltage.

7- Increase the accelerating voltage slowly and notice the periodic recurrent of the collector electrode current as a function of the accelerating voltage. In the voltage range from 0 to approximately 70V, as many as 13 minima are observed. Measurement of these minima which occur in steps of 4.9V with increasing accelerating voltage give a direct measurement of the excitation potentials for mercury.

8- A contact potential of about 2 V exists in the tube between the cathode and the anode, so that the first current minimum lies at about 7 V.

9- A 10k resistor in the anode circuit of the tube prevents overloading of the tube. The tube is thus not endangered even if a discharge by collision ionization takes place in it due to excessively high applied voltage. Thus it is possible to observe the luminous discharge with a spectroscope and to verify from the spectrum that the gas filling is mercury vapor.

**Notes:**

1- You can plot the analogue output of the electrometer (y-axis) against the anode voltage (x-axis) using a digital oscilloscope TDS-340A, store the data then save it on a floppy disc. The data can be taken to computer for data analysis.

2- If any instability occurs at the highest amplification range, it will be found helpful to shield the input plug to the Franck-Hertz tube by wrapping a strip of aluminum foil around the plug and input jack; the foil should be grounded, of course.
Early Ideas about Light Propagation SPEED:

Before the 17th century, scientists believed that there was no such thing as the "speed of light". They thought that light could travel any distance in no time at all. Later, however, several attempts were made to measure that speed, here is summary of progress in measurement of the speed of light.

1- 1667 Galileo Galilei: at least 10 times faster than sound.
2- 1675 Ole Roemer: 200,000 km/sec.
3- 1728 James Bradley: 301,000 km/s.
4- 1849 Hippolyte Louis Fizeau: 313,300 km/s.
5- 1926 Leon Foucault: 299,796 km/s.
6- Today: 299792.458 km/s

1667 Galileo: (at least 10 times faster than sound).

In 1667, Galileo Galilei is often credited with being the first scientist to try to determine the speed of light. His method was quite simple. He and an assistant each had lamps which could be covered and uncovered at will. Galileo would uncover his lamp, and as soon as his assistant saw the light he would uncover his. By measuring the elapsed time until Galileo saw his assistant's light and knowing how far apart the lamps were, Galileo reasoned he should be able to determine the speed of the light. His conclusion: "If not instantaneous, it is extraordinarily rapid". Most likely he used a water clock, where the amount of water that empties from a container represents the amount of time that has passed. Galileo just deduced that light travels at least ten times faster than sound.

1675 Ole Roemer: (200,000 km/sec).

In 1675, a Danish astronomer Ole Roemer noticed (while observing Jupiter's moons) that the times of the eclipses of the moons of Jupiter seemed to depend on the relative positions of Jupiter and Earth. If Earth was close to Jupiter, the orbits of her moons appeared to speed up. If Earth was far from Jupiter, they seemed to slow down. Reasoning that the moons orbital velocities should not be affected by their separation, he deduced that the apparent change must be due to the extra time the light had to travel when Earth was more distant from Jupiter. Using the commonly accepted value for the diameter of the Earth's orbit, he came to the conclusion that light must have traveled at 200,000 km/s.

1728 James Bradley: (301,000 km/s).

In 1728 James Bradley, an English physicist, estimated the speed of light in vacuum to be around 301,000 km/s. He used stellar aberration to calculate the speed of light. Stellar aberration causes the apparent position of stars to change due to the motion of Earth around the sun. Stellar aberration is approximately the ratio of the speed that the earth orbits the sun to the speed of light. He knew the speed of Earth around the sun and he could also measure this stellar aberration angle. These two facts enabled him to calculate the speed of light in vacuum.
1849 Hippolyte Louis Fizeau: (313,300 km/s).

A Frenchman, Fizeau, shone a light beam between the teeth of a rapidly rotating toothed wheel. A mirror more than 5 miles away reflected the beam back through the same gap between the teeth of the wheel. There were over a hundred teeth in the wheel. The wheel rotated at hundreds of times a second - therefore a fraction of a second was easy to measure. By varying the speed of the wheel, it was possible to determine at what speed the wheel was spinning too fast for the light to pass through the gap between the teeth, to the mirror, and then back through the same gap. He knew how far the light traveled and the time it took. By dividing that distance by the time, he got the speed of light. Fizeau measured the speed of light to be 313,300 km/s.

1926 Leon Foucault (299,796 km/s).

Another Frenchman, Leon Foucault, used a similar method to Fizeau. He shone a light beam to a rotating mirror, then it bounced back to a second stationary mirror and then back to the first rotating mirror. But because the first mirror was rotating, the light from the rotating mirror finally bounced back at an angle slightly different from the angle it initially hit the mirror with. By measuring this angle, it was possible to measure the speed of the light. Foucault continually increased the accuracy of this method over 50 years. His final measurement in 1926 determined that light traveled at 299,796 km/s.

Today: (299792.458 km/s).

Today, according to the US National Bureau of Standards, the speed of light is c = 299792.4574 +/- 0.0011 km/s. According to the British National Physical Laboratory, the speed of light = 299792.4590 +/- 0.0008 km/s (making an average with the US standard = 299792.458 km/s).

Measurement of the Speed of light using the Foucault method:

Figure (1) shows an experimental set up like that developed by Foucault in 1862. The basic technique is to send a beam of light on a path so that it bounces between a rotating mirror, a fixed mirror and back to the rotating mirror for a total distance 2D.
The speed of light is calculated by studying the optical path of the light between the two mirrors as follows:

**i) When the rotating mirror (RM) is fixed:**

A parallel beam of light (from the laser) is focused to a point image at S by lens $L_1$. Lens $L_2$ is positioned so that the image point at the rotating mirror is fixed. The basic technique is to send a beam of light on a path so that it bounces between a rotating mirror, a fixed mirror and back to the rotating mirror for a total distance $2D$, as shown in the back along the same path to again focus the image at S.

In order that the reflected point image can be viewed through the microscope, a beam splitter is placed in the optical path, so a reflected image is also formed at point s, just underneath the microscope objective.

**ii) When RM is rotating:**

During the time of flight of light on the path between the two mirrors the rotating mirror will have turned a very slight angle, $\Delta \theta$. This small rotation will deflect the beam of light through an angle of $2\Delta \theta$ from its original path, producing a displacement shift $\Delta S$ proportional to the mirror angular velocity $\omega$ and inversely proportional to the speed of light. As will be shown in the following derivation, by measuring the shift of the image $\Delta S$ (or $\Delta s$), the angular velocity of RM, the distance D and the magnification of $L_2$, we can determine the speed of light.

Figure 2 shows the unfolded optical path (by imagining the rotating mirror to be missing, but still causing the effect).

![Diagram](image)

**Figure (2)**

The displacement of the image is: $\Delta S = 2D\Delta \theta$ and then the apparent displacement $\Delta s$ is given by: $\Delta s = \Delta S \frac{A}{(D+B)}$

Substituting for $\Delta \theta = \omega \Delta \tau$, where $\tau$ is the time of flight $\tau = 2D/c$ yields:

$$\Delta s = \frac{4D^2A\omega}{e(D+B)},$$

The angular frequency $\omega = 2 \pi \gamma$ where $\gamma$ is the frequency of the rotating mirror (in rev/sec) determined by the counter on the rotating mirror controller. $\Delta s$ is measured with a micrometer stage on the microscope, $D$ and $B$ are essentially measured with rulers. The measurement for $A$ is a bit more subtle. Notice in Fig. 2 that the point S is an image of the point $s$ formed by lens $L_2$ which has a focal length $f_2$. From the law of thin lenses:

$$\frac{1}{i} + \frac{1}{o} = \frac{1}{f_2}.$$
Where $i$ and $o$ are image distances and object distances respectively. Substituting $(D + B)$ for $i$ and $A$ for $o$ and rearranging, we have:

$$\frac{l}{A} = \frac{l}{f_o} \cdot \frac{l}{(D + B)}.$$

Solving for $A$ we have

$$A = \frac{f_o(D + B)}{(D + B) - f_o}.$$

**Experimental Set-Up:**
Pasco scientific complete speed of light apparatus includes:

- OS-9262 basic speed of light apparatus, which includes:
  - OS-9263 high speed rotating mirror assembly.
  - Fixed mirror.
  - Measuring microscope.
- OS-9171 0.5 mW He-Ne laser.
- OS-9103 one meter optic bench.
- OS 9172 Laser alignment bench.
- OS—9142 optic bench couplers.
- OS-9133 lens (48 mm focal length)
- OS-9135 lens (252 mm focal length)
- Two OS 9109 calibrated polarizers.
- Three OS-9107 component holders.
- Two alignment jigs.

https://class.phys.psu.edu/p457/experiments/pdf/speedoflight.pdf
**Experimental procedure:**

1. Align the set up starting by the laser, rotating mirror lenses, measuring microscope, and the fixed mirror (See Instruction manual for alignment). Two – three hours are needed to align the set-up for the first time.
2. Record the measures of B and D as shown in figure (1).
3. Warm up the rotating mirror motor (for about 3 minutes) at 600 rev/sec and CW direction of rotation.
4. Slowly increase the speed of rotation and notice how the beam deflection increases. Measuring the micrometer reading for several mirror’s speeds $\gamma_{CW}$.
5. Switch off the motor and record the micrometer reading.
6. Calculate the displacement for each CW speed ($\Delta s_{CW}$).
7. Repeat steps 3-6 for CCW direction of rotation.
8. Calculate the average displacement $\Delta s$ for each rotation speed.
9. Plot the displacement $\Delta s$ vs. speed $\gamma$.
10. From the slope and the equation for the slope, obtain the speed of light and calculate the percent deviation from the textbook value.

Note: when adjusting the micrometer, always rotate the micrometer screw in the same direction (CW) for all readings to avoid backlash.
Experiment # (7)
Specific charge of the electron “e/m”

Objectives:
• Determine e/m
• Confirm negative polarity of the electron
• Deflection of electrons in magnetic field—Lentz’s Law
• Determine magnetic field as function of the acceleration voltage at a constant fine beam diameter

Theory:
Using a gas filled tube, the deflection of electron beams in a uniform magnetic field (with the use of Helmholtz coils) provides a means of quantitatively determining the charge-to-mass ratio of the electron, e/m.

When a charged particle such as an electron moves in a magnetic field in a direction at right angles to the field, it is acted on by a force the value of which is given by:

\[ F = Bev \]  
(1)

Where \( B \) is the magnetic flux density in webers/meter\(^2\), \( e \) is the charge on the electron in coulombs, and \( v \) is the velocity of the electron in meters/sec. This force causes the particle to move in a circle in a plane perpendicular to the magnetic field. The radius of this circle is such that the required centripetal force is furnished by the force exerted on the particle by the magnetic field. Therefore:

\[ \frac{mv^2}{r} = Bev \]  
(2)

Where \( m \) is the mass of electron in kilograms, and \( r \) is the radius of circle in meters. \( r = d/2 \), \( d \) is the diameter of circular trajectory of the electron.

When an electron is accelerated through a potential difference \( V \), it has due to its velocity a kinetic energy of:

\[ \frac{1}{2}mv^2 = eV \]  
(3)

Where: \( V \) is the accelerating potential in volts. Substituting the value of \( v \) from Eq. (3) into Eq. (2) we get:

\[ \frac{e}{m} = \frac{2V}{B^2r^2} \]  
(4)

Thus when the accelerating potential, the flux density of the magnetic field, and the radius of the circular path described by the electron beam are known, the value of \( e/m \) can be computed, and is given in coulombs/kg by Eq. (4) if \( V \) is in volts, \( B \) is in webers/m\(^2\) and \( r \) is in meters.

The magnetic field which causes the electron beam to move in a circular path has the magnetic flux density \( B \) (in webers/m\(^2\)) which, in terms of current through the Helmholtz coils and certain constants of the coil, is expressed;
Where \( N \) is the number of turns of wire on each coil,
\( I \) is the current through coils in amperes,
\( a \) is the mean radius of coil in meters,
\( \mu_0 \) is the permeability of empty space, which is \( 4\pi \times 10^{-7} \) Weber/ampere meter.

Substituting Eq. (5) in Eq. (4) gives

\[
\frac{e}{m} = \left( \frac{3.91}{\mu_0^2 \frac{a^2}{N^2}} \right) \frac{V}{I^2 r^2} = \left( \frac{2.47 \times 10^{12} \frac{a^2}{N^2}}{r^2} \right) \frac{V}{I^2 r^2} \quad (6)
\]

Eq. (6) is the working equation for this apparatus. The quantity within parentheses is a constant for any given pair of Helmholtz Coils. The value of \( r \), the radius of the electron beam, can be varied by changing either the accelerating potential or the Helmholtz field current. For any given set of values, the value of \( e/m \) can be computed.

**Note:** See Supplementary Comments at end of these instructions for Eq. (5) and (6) expressed in the electromagnetic system of units.

**Instructions for Operating:**
1- Cat. No. 623 e. m Vacuum Tube and
2- Cat. No. 621k Helmholtz Coils

**Supplied by W. M. WELCH SCIENTIFIC COMPANY**
Description:
No. 623 elm Vacuum Tube has been designed for determining the ratio of charge to mass of an electron. It may also be used to demonstrate the curving of a beam of charged particles as they pass through a magnetic field, and as an aid in explaining the principle of the mass spectrometer. No. 623A Helmholtz Coils have been designed large and rigid to provide the uniform magnetic field required in the operation of the tube. The axis of the coils may be inclined to the dip angle for quantitative measurements and to a horizontal position for classroom demonstrations.

The tube is essentially the same as one described by K. T. Bainbridge (American Physics Teacher 6, 35, 1938) who states that “Historically the method is of great interest as, in principle, it is the same as that described by A. Schuster in 1890 (Proc. Roy. Soc. 47, 526, 1890) and used by W. Kaufman in 1897 (Wied. Ann. 61, 544, 1897).” The present apparatus is based upon an improved version built and extensively tested by Professor Ralph P. Winch, Williams College, and incorporates various additional improvements developed in our own laboratory.

The beam of electrons in the tube is produced by an electron-gun composed of a straight filament surrounded by a coaxial anode containing a single axial slit. See Fig. 1a and 1b for schematic diagrams of the tube. Electrons emitted from the heated filament F are accelerated by the potential difference applied between F and the anode C. Some of the electrons come out as a narrow beam through the slit S in the side of C. When electrons of sufficiently high kinetic energy (10.4 electron volts or more) collide with mercury atoms, mercury vapor being present in the tube, some of the atoms will be ionized. On recombination of these ions with stray electrons the mercury-arc spectrum is emitted with its characteristic blue color. Since recombination with emission of light occurs very near the point where ionization took place, the path of the beam of electrons is visible as the electrons travel through the mercury vapor.

The magnetic field of the Helmholtz Coils causes the stream of electrons to move in a circular path the radius of which decreases as the magnetic field increases. By proper control of the magnetic field the sharp outer edge of the beam can be made to coincide with any one of five bars spaced at known distances from the filament.

Each coil of the pair of Helmholtz Coils has 72-turns of copper wire with a resistance of approximately one ohm. The approximate mean radius of the coil is 33 centimeters. The coils are supported in a frame which can be adjusted with reference to the dip angle so that their magnetic field will be parallel to the earth’s magnetic field but oppositely directed. A graduated scale indicates the angle of tilt. A safety device prevents the coils from accidentally dropping back to the horizontal. Wooden seats with retaining straps cradle the tube in a central plane midway between the two coils.
Fig. 1a is a sectional view of the tube and filament assembly. Fig. 1b is a detailed section of the filament assembly at right angles to Fig. 1a.

A. Five cross bars attached to staff wire.
B. Typical path of beam of electrons.
C. Cylindrical anode.
D. Distance from filament to far side of each of the cross bars.
E. Lead wire and support for anode
F. Filament.
GG. Lead wires and supports for filament.
LL. Insulating plugs

**Accessory Apparatus**
The following apparatus will be needed to perform this experiment. Most of it, or the equivalent, will normally be already on hand. See circuit diagrams. Fig. 2 and Fig. 3.

**Filament Circuit**
1- A 0-8 V DC power supply.
2- D.C. ammeter, 10 ampere range.

**Note: Filament current must be less than 4.5 A**

**Accelerating Circuit**
1- 0: 60V DC power supply.
2- D.C. Mili-ammeter, 25 mA range.
3- High-resistance D.C. Voltmeter, 50 volt range.
Field Circuit
1- 0 : 20 V DC power supply.
2- D.C. Ammeter, 5 ampere range.

Setting Up the Apparatus:
The Helmholtz-Coils assembly may be partially “knocked down” for shipment. The parts removed are a long slotted and graduated strip attached to a flush plate, a right angle casting with clamp, and a rubber bumper. The rubber bumper is to be located on the base board so it will be beneath the bumper on the hinged board. The flush plate is attached to the base board in its place located by the three screws. The right-angle casting with clamp is attached to the under side of the hinged board. This is to be used as a friction brake and should be so regulated that if the clamp screw is loosened while the e/m tube is mounted, the hinged board will settle slowly without shock.

The room should be fairly well darkened for demonstrating and making measurements with the e/m tube. If a table about 16 inches high is available, its use will permit the observer to lean over the Helmholtz Coils and view the beam perpendicular to its plane. If the coils are placed on a table of normal height the observer will have to stand on a chair to see the beam from the proper direction. The wooden box used for shipping the coils is of the right height to make a good support on which to place the apparatus. Its use is suggested if a table or other support is not available.

Place the tube in its support in the center of the frame. The end of the tube from which the leads extend should be adjacent to that part of the frame on which connectors are mounted. Secure the tube in place with the straps.
Orient the Helmholtz Coils so that the elm tube will have its long axis in a magnetic north-south direction as determined by a compass. Measure the magnetic inclination at this location with a good dip needle. Tip the coils up until the plane of the coils makes an angle with the horizontal equal to the complement of the dip angle. The axis of the coils should now be parallel to the earth’s magnetic field.

Make electrical connections to the tube as shown in Fig. (2) and make electrical connections to the Helmholtz Coils as shown in Fig. 3. The ammeter used in this circuit for measuring the field current should have 0.5% accuracy or better. The two coils are connected in series and the current sent through them in such a direction that their magnetic field is oppositely directed to the earth’s field.

**Operation**

The filament of the e/m tube has the proper electron emission when carrying 2.5 to 4.5 amperes. Exceeding 4.5 amperes will materially shorten the tube’s life. Good results can be obtained using an accelerating voltage of 22½ to 45 volts. An electron emission current of 5 to 10 ma gives visible beam. For maximum filament life operate the tube with the minimum filament current necessary for proper electron emission. It is helpful and good practice to apply about 22½ volts accelerating potential to the anode before heating the filament. Always start with a low filament current and carefully increase it until the proper electron emission is obtained. Since the electron beam appears suddenly it is advisable to increase the filament current slowly to avoid overheating and possible burning out the filament.

Apply 22½ volts accelerating potential to the tube. With maximum resistance in the filament circuit, close the switch in this circuit. Gradually decrease this resistance until the milli-ammeter indicates 5 to 10 ma and the electron beam strikes the tube wall. Rotate the tube in its cradle until the electron beam is horizontal and the bars extend upward from the staff wire. Note that the electron beam is deflected slightly toward the base of the tube by the earth’s magnetic field.

Now send a small current through the Helmholtz Coils. If the magnetic field of the coils straightens the beam or curves it in the opposite direction, the coils are correctly connected. If this field increases the deflection toward the base, the current is flowing through the coils in the wrong direction and the connections must be reversed. If no effect is observed on the beam, the field due to one coil is opposing that of the other and connections to one coil must be reversed. Make any necessary changes and increase the field current sufficiently to cause the beam to describe a circular path without striking the wall of the tube. The apparatus should now be ready (or obtaining the necessary data to compute the value of e/m.

**Data and Results:**

In the manufacture of the e/m tubes the crossbars have been attached to the staff wire and this assembly attached to the filament assembly in precise fixtures which accurately control the distances between the several crossbars and the filament. Distances given are to the far side of the crossbar.
Crossbar Number | Distance to Filament (D)
---|---
1 | 0.065 meter
2 | 0.078 meter
3 | 0.090 meter
4 | 0.103 meter
5 | 0.115 meter

These distances are the diameters of the several circles which the electron beam will be caused to describe.

Following the prescribed procedure, heat the filament until the electron beam is visible. Allow a few minutes for warm up and temperature equilibrium. Close the circuit comprising the Helmholtz Coils and adjust the value of the current until the electron beam is straight. One method is to adjust the beam until it is aligned with a straightedge held as close to the tube as possible. Another method is as follows. Increase the current through the coils until the beam shows a slight curvature as compared with the straightedge and record the value of the current. Then decrease the current until the beam shows an equal curvature in the opposite direction and record the current. The average of these values will be the value of the current required to straighten the beam. This adjustment should be made carefully and accurately. When the beam is straight the magnetic field of the coils just equals the earth’s magnetic field. Record the value of this current as $I_1$ in a table similar to Table I. The value of $I_1$ is constant as long as the accelerating voltage, $V$, remains the same. When $V$ is changed the value of $I_1$ must be re-determined.

<table>
<thead>
<tr>
<th>Crossbar No.</th>
<th>$r$</th>
<th>$V$</th>
<th>$I_1$</th>
<th>$I_2$</th>
<th>$I$</th>
<th>$e/m$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Increase the field current until the electron beam describes a circle. Adjust its value until the sharp outside edge of the beam strikes the outside edge of a crossbar. Record this value as $I_2$ in the table. The outside edge of the beam is used because it is determined by the electrons with the greatest velocity. The electrons leaving the negative end of the filament fall through the greatest potential difference between filament and anode and have the greatest velocity. It is this potential difference which the voltmeter measures.

Determine and record the field current required to cause the electron beam to strike each of the other bars. Subtract $I_1$ from each value of $I_2$ and record as $I$. 

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This is the value of the current to be used in Eq. (6) for computing $e/m$. Compute $e/m$ for each value of $I$.

Repeat the above and determine $e/m$ using a different value of accelerating voltage such as 45 volts. Compare the results with the accepted value of $e/m$, which is $1.76 \times 10^{11}$ Coulomb/kg.

**Supplementary Comments**

By subtracting the field current just necessary to overcome the earth’s field from the total field current required to curve the beam into a given circular path, the effect of the earth’s field on the determination of $e/m$ is eliminated and there is no need to know or otherwise determine the earth’s magnetic field. However, if desired, the value of the earth’s magnetic field may be computed using the value of $I_1$, in Eq. (5).

The tube can be used quite effectively as a demonstration in a well-darkened lecture room. For the most effective demonstration the whole unit should be tipped until the axis of the coils is nearly horizontal. In this position the tube and the beam of electrons are most easily seen by the class.

The action of this $e/m$ tube and Helmholtz Coils can be used in explaining the principle of a mass spectrometer. A consideration of Eq. (6) shows that for charged particles carrying the same charge but differing in mass the radius of the circular path into which they are caused to move by the magnetic field differs for particles of different masses. Knowing the value of the charge and measuring the radius of the circular path, the mass of particles can be determined. This is essentially what is done in a mass spectrometer.

If the magnetic field of the Helmholtz Coils is increased sufficiently to cause the electron beam to describe a circle of small radius, then by rotating the tube slightly the beam will spiral either upward or downward. Reversing the filament current will reverse the direction of the spiral, the spiraling of the beam being caused by the magnetic effect of the filament current. A reversing switch in the filament circuit is helpful during this demonstration.

In the electromagnetic system of units, Eq. (5) is

$$B = \frac{32\pi NI}{\sqrt{125a}}$$

And Eq. (6) becomes

$$\frac{e}{m} = \left(2.47 \times 10^{-2} \frac{a^2}{N^2}\right) \frac{V}{I^2 r^2}$$

Where $a$ and $r$ are in cm, $V$ is in abvolts, $B$ is in gauss, and $I$ is in abamperes. In this system the accepted value of $e/m$ is $1.76 \times 10^7$ abcoulombs/gram.
Two Helmholtz coils are mounted on a base to position the electron tube socket in the uniform part of the field. These coils are wound on aluminum rings with rims milled on both ends, to make it easy to find their mean diameter. Each one is stamped with the number of turns of wire wound around it (119), and has a rated carrying capacity of 4 amperes. You can attach accessories and power supplies to the base with the six built-in binding posts. The uniquely designed tube socket lets you adjust the tube within the magnetic field to give precise results.

The most important part of this apparatus is the special electron beam tube. This oversized tube features a clearly marked circular target with concentric circles precisely marked on it. Their radii (0.5, 1.0, 1.5, and 2.0cm) also are precisely marked. The inscribed radii have a phosphor filling that fluoresces when the electron beam strikes it, to aid in accurate adjustment. When the beam enters the magnetic field, it will curve. All you have to do is adjust the strength of the magnetic field so the beam falls on one of the circles, and you can easily find its radius of curvature. Simply measure or calculate the other values you need, and this radius measurement gives you the ratio e/m. You'll need to add a power supply and a multimeter.

**Specifications:**
Typical accelerating voltage: Under 200V  
Typical field strength of coil: 2 x 10^-3Wb/m^2 with a current of about 4A  
Number of turns on coils: 119

**Dimensions:**  
Base: 27.9(L) x 14cm (W)  
Coil diameter: 22.9cm  
Distance between the center of the coils: 10.2cm
THE DOUBLE BEAM TUBE TEL 534

The Double Beam Tube TEL 534 comprises two adjacent and independent diode electron guns with deflector plates attached, and a common deflector electrode mounted within a clear glass bulb containing helium at low pressure. Part of the glass bulb is coated with a luminescent screen.

Both guns comprise an indirectly heated oxide cathode ad a conical anode so arranged that the narrow electron beams are projected
1. diametrically across and
2. Tangentially with respect to the spherical bulb.

The beams emit dominantly green light. The diametrical beam impinges on the luminescent screen. The heaters are connected to a two-way switch and two 4mm sockets in the base cap.

The common anode connection is made to a 4mm plug mounted on a plastics cap on the neck and the common deflector electrode is connected to a similarly located 4mm plug.

**Experimental Apparatus**

Double Beam Tube TEL 534  
Helmholtz Coils TEL 502  
L.T.Power Unit TEL 800  
Universal Stand TEL 501  
H.T.Power Unit TEL 801  
3 Digital Multimeters

*Note that* the use of grey plastic for the caps signifies that the tube contains gas (black plastic is used for vacuum tubes).

**Electrical Supplies:**

- Heater Voltage: 5-7 V 0.3 A.
- Anode Voltage: 0-300V d.c. 30mA (MAX)
- Deflector Voltage: 0-25V d.c. or higher or A.C
- Helmholtz Coils: 10-15V 1-1.5 A

**Technical Notes:**

ALWAYS REDUCE ANODE VOLTAGE TO ZERO BEFORE SWITCHING ON A HEATER SUPPLY.

The anode current should always be monitored and should be reduced as much as possible consistent with maintenance of adequate intensity and path length. Currents typically range from 10-30mA. Note that the regulation of some power packs can cause the output voltage to fall as the beam current increases, with consequent decrease of path length.

The anode current is determined largely by the temperature of the cathode and some adjustment to the heater voltage of a particular gun may be advantageous, i.e. increase or decrease voltage over range 5V—7V: e.g. it may be sufficient to operate at 6.0V instead of 6.3V.

The length of beam depends on the anode voltage and about 100V is required to traverse the diameter of the bulb.

Check that the negative H.T. lead is connected to the common heater and cathode socket, by deflecting the beam with a magnet. If wrongly connected, the modulation of the anode voltage by the A.C. heater current will cause the beam to fan out slightly.
Diametrical Beam:
Unless the anode voltage is 100V, the phosphor may not luminescence. Further, due to charge build—up on the surface, luminescence may not occur until the beam is displaced. The beam is slightly curved due to the earth’s magnetic field.

Tangential Beam:
To adjust the plane of the ‘circular path’ of the beam when the Helmholtz Coils are used, rotate the jaws of the Universal Stand within the limits of the coils. To measure the diameter of the curved path, adjust the field current and anode voltage so that the beam touches the plane defined by the circular edge of the phosphor screen. The distance between this plane and the gun can be made with a traveling microscope or by the mirror and ruler technique.

Please note that:

i) The double beam tube should be aligned in a direction to minimize the spiraling of the beam caused by the earth’s magnetic field.

ii) Power supplies and meters should be kept somewhat remote from the apparatus because of their magnetic fields.

iii) The anode current can range from 10 to 30 mA but it is preferable to run at the lower end of this range to enhance tube life.

iv) The heater voltage should be monitored and should be limited to 6.0 volts.

v) For this experiment we will use the tangential beam.

vi) The current in the Helmholtz coils should be limited to 1.0 Amp. It is the outermost portion of the electron beam that is used in this experiment.

vii) Application of a small p.d. between the deflector plates sometimes enhances the sharpness of the beam. Whilst a deflector voltage of 25V is suggested, higher voltages - d.c. and a.c.- can be used.
**Exp # (8)**

**Micro-wave Optics**

**Introduction to Microwave Optics:**
Microwaves are electromagnetic waves with wavelengths shorter than one meter and longer than one millimeter, or frequencies between 300 megahertz and 300 gigahertz. In the electro-magnetic spectrum microwaves are located between UHF radio waves at one extreme and the far infrared at the other.

Because microwave wavelengths are usually comparable to or smaller than the ordinary physical dimensions of objects interacting it, microwaves behave like light waves. The term optics is appropriate because many phenomena observed with visible light can be studied with microwaves. A beam of microwaves propagates along a straight line, in a perfectly homogeneous infinite medium. Effects of reflection, polarization, interference, diffraction, scattering, and atmospheric absorption usually associated with visible light are of practical significance in the study of microwave propagation.

Making an experiment with microwave, with a wavelength of about 3 cm, radically changes the scale of the experiment. Microns become centimeters and traditional optics experiment are easily seen and manipulated. The large wavelength makes it easy to understand and visualize electromagnetic wave interactions. Interference and diffraction slits are several centimeters wide, and polarizers are slotted sheets of metals e.g. stainless steel. The large scale of the experiments makes the details of the wave interactions easy to visualize and to understand.

**Microwave Sources and Detectors:**
The first essentials for an experimental study of microwaves are the source and the detector. Ordinarily radio and TV transmitters and detectors usually incorporate oscillators using LC resonant circuits along with transistor or vacuum-tube amplifiers. There are several reasons why it is not practical to build such oscillators for frequencies greater than a few hundred megahertz (1 MHz = $10^6$ Hz = $10^6$ cycles/sec). A major difficulty exists due to small, but unavoidable, capacitances between electrodes and their associated connections in vacuum tubes and transistors. Since the ac impedance of a capacitor varies inversely with frequency, such stray-capacitances act as short circuits at sufficiently high frequency. A second kind of difficulty arises when the transit-time for electrons in the device becomes comparable to the period of the high-frequency signal.

**Sources:**
Most of practical microwave sources are Vacuum tube based devices operating on the ballistic motion of electrons in a vacuum under the influence of controlling electric and magnetic fields. They include the devices known as Magnetrons, Klystrons, Traveling wave tubes (TWT), and Gunn Diodes. These devices work in the density modulated mode, rather than the current modulated mode. This means that they work on the basis of clumps of electrons flying ballistically through them, rather than using a continuous stream.
2K 25 Reflex Klystron:
A low-voltage reflex klystron RK2K 25 is used as a low-power microwave source in these experiments. The device can be mechanically tuned with the screw on the left, which applies vertical compression to the metal envelope between 8.5 and 9.6 GHz, (corresponding to wavelengths of 3.5 to 3.1 cm) as shown in Figure (1).

In this device the conventional LC resonant circuit is replaced by a doughnut-shaped structure called a cavity. The two grids act as the plates of a capacitor, and the surrounding torus as a one-turn inductor. In operation, charge flows back and forth from one grid to the other through the outside surface of the cavity, and the device acts as an LC circuit.

![Figure 1](image1.png)

The Reflex Klystron 2K 25

This oscillating current flow is accompanied by oscillating electric and magnetic fields between the grids and inside the cavity. These consist principally of an electric field between the grids and a magnetic field inside the doughnut, as shown in Figure (2). If the charge and current oscillate in a sinusoidal way, then so do the fields. Since the charge and current are a quarter cycle out of phase, we also expect the electric and magnetic fields to be a quarter cycle out of phase. Figure (2) shows the approximate field configurations and the charges and currents during various parts of the cycle.
Oscillations in an LC circuit do not continue forever, but are damped by the energy loss due to resistance which is always present in the circuit. Similarly, oscillations in the Klystron are damped by energy loss through radiation and currents in the cavity wall. The problem is to feed back energy into the oscillating field to compensate for these losses and permit sustained oscillations. This is accomplished by means of an electron beam passing through the grids. Electrons are emitted continuously by the cathode and are accelerated by the field between cathode and cavity. As they pass through the alternating field between grids, some electrons are accelerated, others slowed down, depending on the phase of this oscillation when they arrive. As a result, some electrons drift forward and some backward in the beam, relative to the average beam velocity. The result is a bunching of electrons at certain positions along the beam.

![Figure 2](image)

Figure (2) Field oscillations in the reflex klystron

After passing through the screens, the entire beam is stopped and reversed by the negative potential on the reflector electrode (hence, the term reflexes klystron). The bunched beam returns to the grids in the font of a series of pulses of electrons, arriving with the same frequency as that of the oscillation. Now if the reflector voltage is properly adjusted, these pulses return again at a time in the cycle such that they are retarded by the alternating field between grids; the energy lost by the electrons goes into the oscillating field, and hence provides the mechanism for feedback of energy into the oscillations with the correct frequency and phase. The crucial factor is the time that the electron bunch requires for the round trip; this, in turn, is determined by the beam and reflector voltages, and so it is not surprising that the klystron will oscillate only with certain combinations of these two voltages. However, for a given beam voltages there are several possible values of reflector voltage which give the correct phase relation.
To draw microwave power out of the klystron, a small coupling loop is inserted in the cavity. The oscillating magnetic field in the cavity induces a voltage in this loop; the resulting microwave current flows down a coaxial output lead to an output antenna, which radiates into a waveguide and finally into the output horn. The output from the horn, at sufficient distances, is approximately a plane wave.

The necessary voltages are supplied by connecting the klystron as shown in figure (3) to the regulated power supply according to the given specifications:

**Heating Supply:**
\[V_f = 6.3\text{V DC. Regulated (\pm 5\%)}\]
\[I_f (\text{max 440 mA)}\]

**Resonator (Beam) Supply:**
\[V_0 = 300\text{V DC (max 330V)}\]
\[I_0 = 22\text{ mA (max 37 mA)}\]

**Repeller Supply:**
\[V_R = -150\text{V DC (-130: -190 V)}\]
\[I_R = 3\text{ mA}\]

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**Microwave Detectors:**

Microwave detection uses a principle very similar to that of detectors in ordinary AM radio receivers. We use a semiconductor diode which conducts preferentially in one direction. At microwave frequencies the junction capacitance acts to filter the rectified signal, so that the terminal voltage of the diode is a dc voltage which depends on the amplitude of the microwave signal.

At small amplitudes the diode voltage is approximately proportional to microwave intensity (power per unit area); this, in turn, is proportional to the square of the E-field amplitude. At higher levels the diode voltage becomes more nearly proportional to the E-field amplitude itself. This voltage is measured with an ordinary high-impedance...
voltmeter such as a vacuum-tube voltmeter or an oscilloscope. By the nature of the device, the diode is sensitive only to the component of E-field along its axis; thus it can also be used as an indicator of the polarization of the wave. The diode is mounted in the waveguide of a receiver horn, which restricts the solid angle of acceptance.

Experiments:
1- Measuring beam intensity and profile.
2- Reflection and refraction.
3- Standing waves, measuring wavelength.
4- Polarization.
5- Diffraction by a periodic structure.
6- Double slit interference.
7- Michelson’s interferometer.

Experimental pre set-up:
1- Mount the microwave transmitter and detector facing each other on the arms that rotate about the graduated circle (Goniometric).
2- Connect the Klystron to the DC power supply. Use an accelerating voltage of 300V and a reflector voltage of about -150V. The electron current should be about 25ma.
3- Connect the detector should to a high impedance DC voltmeter.

Exp. (1); Measuring beam intensity and profile

Needed Equipment:
- Transmitter.
- Receiver.
- Goniometer
- Meter stick.

Procedure:
1- Arrange the Transmitter and Receiver facing each other on the Goniometer arms as shown in figure (4). Adjust both transmitter and receiver to the same polarity.
2- Adjust the transmitter and receiver so the distance between them “d” is about 30 cm.
3- Adjust alignment to obtain max output.
4- Increase the distance d in steps of 5 cm and measure the corresponding output.
5- Plot a relation between the receiver output and 1/d².
6- Shows that the intensity is related to the inverse square of the distance between the transmitter and the receiver.
7- To measure the beam profile Adjust d = about 1.0 m.
8- With transmitter angle fixed change the angle of the receiver in both directions, and then measure the intensity at each angle. Plot the received intensity as a function of angle, the beam has a roughly Gaussian output distribution.

9- Determine the angular beam width (where the intensity falls to 1/e of its maximum value).

**Exp. (2): Reflection and refraction**

**Needed Equipment:**
- Transmitter.
- Receiver.
- Goniometer.
- Metal reflector.
- Metal Reflector.
- Right angle Styrofoam prism.

**Procedure:**

1- To study reflection; arrange the Transmitter and Receiver on the Goniometer arms as shown in figure (6).
2- Adjust the Angle of Incidence (between the incident wave and a line normal to the plane of incidence) to be 20°.
3- Rotate the arm of the receiver to get maximum output then record the angle of reflection.
4- Repeat steps 2 and 3 for angles of incidence 25, 30, 35, ……, 80°.
5- Plot the angle of reflection as a function of the angle of incidence.
6- Write your conclusions about Snell’s law for reflection.
7- To study refraction; first align the transmitter and receiver for max output, measure receiver angle.
8- Place the right angle prism with its hypotenuse perpendicular to the incident wave as shown in figure (7).
9- Rotate the receiver till receiving maximum output, then measure the receiver angle again.
10- Knowing the prism angle, calculate the angles of incidence and refraction.
11- Use Snell’s law for refraction to calculate the refractive index of prism material.
Exp. (3): Standing waves, measuring wavelengths.

**Needed Equipment:**
- Transmitter.
- Receiver.
- Goniometer.
- A wet thin sheet of balsa wood.

**Idea of the experiment:**
When the transmitter and receiver horns face each other, some of the wave is reflected back by receiver horn. The superposition of the reflected and incident waves produces standing waves forming nodes and antinodes. The distance between two successive nodes (or antinodes) equals to half the wavelength.

The standing-wave pattern can be observed as follows: Insert a thin sheet of plywood between the two horns. Part of the wave is absorbed by the wood, part transmitted and part reflected. Absorption will be greatest when the wood is near antinodes in the standing-wave pattern, and least when it is near a node. Thus when the wood is moved along the axis, the intensity measured by the detector will vary in a cyclic manner.

**Procedure:**
1. Arrange the microwave transmitter and receiver facing each other about 1 m apart.
2. Adjust the reflector voltage for the microwave klystron until a maximum in output is detected.
3. Adjust the distance between transmitter and detector by a few cm until the strongest signal is detected at the receiver. In this situation, a standing wave pattern is in the space between the transmitter and receiver.
4. Mount a thin wet sheet of balsa wood between the transmitter and receiver.
5. Change the position of the sheet of wood and notice the strong variations in the strength of the signal received.
6. Measure the positions of several consecutive maxima and minima.
7. Determine the wavelength, and from it calculate the frequency of the klystron.

Exp. (4): Polarization.

The microwave radiation from the Transmitter is linearly polarized i.e., as the radiation propagates through space, its electric field remains aligned. If the axes of the transmitter and receiver were aligned vertically, the electric field of the transmitted wave would be vertically polarized and totally received by the detector. If the detector diode were at an angle $\theta$ to the transmitter axis, as shown in Figure (8), it would only detect the component of the incident electric field that was aligned along its axis.

In this experiment you will investigate the phenomenon of polarization and discover how a polarizer can be used to alter the polarization of microwave radiation.
**Needed Equipment:**
- Transmitter.
- Receiver.
- Goniometer.
- Polarizer.

**First Procedure:**
Loosen the hand screw on the back of the Receiver and rotate the Receiver in increments of ten degrees.
1- By changing the orientation of the detector horn, show that the microwaves are plane-polarized.
2- By observing the orientation of the diode in the detector, determine the plane of polarization.
3- Measure the detected signal as a function of detector horn angle.

Can you predict what the functional relationship should be? (Malus Law).

**The Polarizer:**
The metal grids which are provided act like polarizing filters with a light beam. Transmission through the grid is almost 100% when the E vector is perpendicular to the slots, but much less than 100% when parallel.
Can you understand this behavior on the basis of current induced in the grids? Verify this behavior of the grids experimentally.

**Second Procedure:**
1- Reset the Receivers angle to 0-degrees so maximum signal is received.
2- Place the polarizer, and record the meter reading when the Polarizer is aligned at 0, 22.5, 45, 67.5 and 90-degrees with respect to the horizontal then remove the polarizer slits.
3- Rotate the Receiver so the axis of its horn is at right angles to that of the Transmitter so a zero (minimum) signal is received. Record the meter reading.
4- Replace the Polarizer slits and record the meter readings with the Polarizer slits at 0, 22.5, 45, 67.5 and 90-degrees with respect to the horizontal.

What will be the polarization of this signal? Test your predictions experimentally. Is it possible to modify the polarization plane of the microwaves by inserting anything between source and detector? Try a few things.

**Exp. (5); Diffraction by a periodic structure**

**Introduction to Bragg’s Law**
In 1914, the Nobel Prize for physics was awarded to Max Von Laue for his discovery of the diffraction of X-rays by crystals. Just as visible light can be diffracted by the regular, parallel grooves on a diffraction grating, the regular arrangement of the atoms in a crystal act to diffract the shorter wavelength X-rays. In order to observe diffraction in
reflected (or scattered) light, the distance between grooves on a diffraction grating must be on the order of the wavelength of the light. The distance between atoms in a crystal is on the order of the wavelength of X-rays, so that the crystal becomes a “grating” for the X-rays.

Analogy with diffraction of light by a grating: When light passes through an ordinary diffraction grating you observe bright and dark interference fringes corresponding to regions of constructive and destructive interference, as illustrated in figure (10).

The positions (angle $\theta$) of the bright and dark fringes are given by:

- $n \lambda = d \sin \theta$ (bright fringes)
- $(n + \frac{1}{2}) \lambda = d \sin \theta$ (dark fringes)

Where $d$ is the grating spacing and $n$ is the order of the interference maximum or minimum. Thus for the central bright fringe, $n = 0$. In the diagram, $n = 2$, because $\theta$ is the angular position of the second order bright fringe (interference maximum).

Figure (10)

Bragg’s Law for reflection (scattering): Similarly, a crystal for which the atomic spacings are known can be used to determine the wavelength composition of X-rays. However, the most important application of X-ray diffraction from crystals is to use X-rays of known wavelength to determine the unknown spacings between atoms in the crystals. X-ray scattering, sometimes referred to as Bragg diffraction, is widely used in basic crystallographic structure analysis, analysis of material composition, the analysis of stress and strain conditions within crystalline material, and the study of macromolecular systems by molecular biologists.

Bragg’s law is derived by considering the reflection (scattering) of monochromatic electromagnetic waves of wavelength $\lambda$ from successive planes of atoms.

The reflection from successive planes will interfere constructively if the total difference $\delta$ in optical path lengths for waves reflected from planes 1 and 2 is an integral number of wavelengths.

Figure (11)
If the spacing between the indicated planes is $d$ and the incident beam makes an angle $\theta$ with these planes then the path length difference is given by

$$\delta = d (\sin \theta + \sin \theta')$$

We assume that $\theta = \theta'$, the law of specular reflection. It follows that:

$$2d \sin \theta = n \lambda$$

Where $n = 1, 2, 3, \text{etc.}$

For this experiment we use microwaves instead of X-rays. We use a Styrofoam block imbedded with a cubic lattice of metal spheres as a simulated “crystal”. The spacing between the metal spheres is on the order of the wavelength of the microwaves so that the Bragg’s law ($2d \sin \theta = n \lambda$) can easily be satisfied.

**Needed Equipment:**
- Transmitter.
- Receiver.
- Goniometer.
- A styrofoam block imbedded with a cubic lattice of metal spheres.

**Procedure:**
1. Do experiment (3), (6) or (7) to determine the wavelength of the microwaves.
2. Arrange the transmitter, receiver and crystal on the Goniometer as in figure (11). Make intensity versus $\theta$ plot.
3. Determine the reflections off the (100) plane of scatters.
4. Repeat your arrangement to measure scattering reflection angles for the planes (110) and (210) as shown in figure (12).
5. From your data, calculate the spacing between planes in the crystal. Compare with a direct measurement of the side of the unit cube formed by the metal balls.

**Note that:** both the receiver and transmitter positions must be changed between readings to keep the angles of reflection and incidence equal.
Exp. (6): Double slit interference (Young’s Experiment).

**Needed Equipment:**
- Transmitter.
- Receiver.
- Goniometer.
- Double slits aperture.

![Figure (13, a, b)](image)

**Introduction:**
The double slit experiment (Young’s experiment) is one of the simplest experiments to show interference of waves. The wave front of the incident wave is divided into two coherent outputs by the two symmetrically placed slits. Beyond the two-slit aperture the two beams interfere forming the well known young’ interference pattern. It was proved that the intensity of the wave beyond the aperture will vary according to the angle of propagation such that:

\[ d \sin (\theta_n) = n\lambda \]

Where \( d \) is the slit separation distance, \( \theta_n \) = the angle of propagation (detection), \( \lambda \) = the wavelength of the incident radiation, and \( n \) is an integer called the order of interference (See Figure 13-a).

**Procedure**
1. Arrange the equipment as shown in Figure 13-b. Use the first double slit aperture with slit width of about 1.5 cm and slit separation \( d = 6.5 \) cm.
2. Adjust the Transmitter and Receiver for vertical polarization (0°).
3. Rotate the rotatable Goniometer arm (on which the Receiver rests) slowly about its axis.
4. Measure the detector output at different angles in both directions then determine \( \theta_1, \theta_2 \) and \( \theta_3 \) (if possible).
5. Repeat the experiment using the second and third double slit apparatus with \( d = 8.5 \) and 10.5 cm respectively.
6. Write your comments about the results.

Exp. (7): Michelson’s interferometer.

**Introduction**
Michelson interferometer is one of the simplest two beams interferometers based on amplitude division technique. As seen in figure (14) the amplitude of incident beam is spited using a partial reflector (C) into two perpendicular beams. The first is called the reference beam that is reflected by a fixed reflector (B) while the second is called the sensing beam. The reflector (A) that reflects back the sensing beam can move along the second arm of the interferometer. The two reflecting beams superimpose again at the partial reflector forming interference pattern.
Microwaves travel from the Transmitter to the Receiver over two different paths. In one path, the wave passes directly through C, reflects back to C from A, and then is reflected from C into the Receiver. In the other path, the wave reflects from C into B, and then back through C into the Receiver. If the two waves are in phase they interfere constructively and when they reach the Receiver, a maximum signal is detected. But if the two waves are out of phase (180° phase difference) they interfere destructively and when they reach the Receiver, a minimum signal is detected. By moving the Reflector (A), the path length of one the path length of one wave changes, thereby changing the phase difference at the Receiver so a successive maxima and minima are detected. Since each wave passes twice between a Reflector and the Partial Reflector, moving the Reflector (A) a distance \( d = \frac{\lambda}{2} \) will cause a complete 360-degree change in the phase of one wave at the Receiver. This causes the meter reading to pass through a minimum and return to a maximum again.

**Needed Equipment:**
- Transmitter.
- Receiver.
- Two perpendicular Optical rails
- Two Metal reflectors.
- One partial reflector

![Figure (14)](image)

**Procedure:**
1. Arrange the experiment as shown in Figure (14).
2. Plug in the Transmitter and adjust the Receiver for an easily readable signal.
3. Slide Reflector A along the arm and observe the relative maxima and minima of the meter deflections.
4. Set Reflector A to a position which produces a maximum meter reading. Record, \( X_1 \), the position of the Reflector.
5. While watching the meter, slowly move Reflector A away from the Partial Reflector until the meter reading has passed through at least 10 minima and returned to a maximum.
6. Record the number of minima that were traversed also record \( X_2 \), the new position of Reflector A.
7. Calculate the wavelength of the microwave radiation \( \lambda = \frac{(X_2 - X_1)}{5} \).
8. Repeat the experiment beginning with a different position for Reflector A.
Exp # (9)

Electron Diffraction

All fundamental entities that make up the world have both wave and particle characteristics. Electromagnetic radiation or “light,” first revealed its wave nature in diffraction experiments, exhibiting constructive and destructive interference, a characteristic only of waves. Later (1905) studies of the photoelectric effect revealed the particle-like (photon) aspect of light.

Other entities, such as electrons, protons, neutrons, etc., were, for a time following their discovery, considered only as particle-like objects. Later, experiments revealed their wave nature. The classic experiment by Davidson and Germer in 1927 first revealed the wave nature of the electron. In this experiment, electrons were scattered from a crystal, and diffraction effects (constructive and destructive interference) were observed. The atoms within a crystal provided multiple scatterers, and they were separated by a distance comparable to the wavelength of the electron waves, thus satisfying the condition for observing interference phenomena.

You should note that, in this experiment, the interference is observed even if the intensity of the electron beam is so low that (momentarily reconsidering the electron as a particle) only one electron at a time reaches the crystal. Thus the interference is not between one electron and another electron, but occurs for each electron.

OUTLINE OF THE EXPERIMENT:

You will observe electron diffraction, and measure the wavelength of the electron. You will use the model TEL 555 electron diffraction tube, in which an electron gun emits electrons of mass m and charge e which are accelerated through an electrical potential difference V, acquiring a kinetic energy K:

\[ K = eV = \frac{1}{2} mv^2 = \frac{p^2}{2m} \]  

(1)

These electrons impinge on a crystal; the crystal is a thin layer of graphite carbon. The surface layer of atoms in the crystal acts as a grating of ruling-spacings 1.23 and 2.13 Angstroms. The resulting interference pattern exhibits first order diffraction maxima whenever the following condition is met:

\[ \lambda = d \sin \theta \]  

(2)

You will measure \( \theta \) and compute \( \lambda \), using the above equation. You will then compare your result to the theoretical value of \( \lambda \) computed from the expression first put forward by Louis de Broglie in 1924, and substantiated by many experiments since:

\[ \lambda = \frac{h}{p} \]  

(3)

Where h is Planck’s constant and p is the momentum of the electron. Substituting for p in equation 3 (using Eq. 1), we see that the theoretical wavelength is
\[ \lambda = \frac{h}{\sqrt{2eVm}} \]  

(4)

**PROCEDURE:**
Read the reference material on electron diffraction, from *Modern Physics* by Sproul & Phillips, and/or other sources. Be sure you can derive the relevant equations. You will do so in your report. Be sure you understand why the interference pattern, consists of circular rings.

1. Read the manufacturer’s instructions on the TEL 555 tube. We will not be following the manufacturer’s procedure but reading this material will help to familiarize you with the apparatus. It helps to know that the word “tension” is used for what we call “voltage” in the literature from this manufacturer (e.g., ht is the abbreviation for high voltage).

**Apparatus:**

Electron Diffraction Tube TEL 555  
TEL. 813 kV power unit  
Set of connectors

2. Connect the circuit as per the diagram below. The wire from the negative high voltage to the base of the tube has a special small connector on the end which goes into the base of the tube. Note that we will not be doing the external biasing indicated in the manufacturer’s literature.

![Diagram of circuit](image)

The 6.3 Vac is connected to the base of the tube using the large plugs, the -HV is connected to the base of the tube using the small plug, and the +HV is connected to the neck of the tube using a connector that completely covers this plug with no bare connector showing, this point reaching several thousand volts during the experiment!
3. With the accelerating voltage set at zero, turn on the power unit. The cathode heater should glow a dull red inside the base of the tube, it should not approach white hot which would evaporate the heater wire and render the tube useless. Slowly turn the accelerating voltage upward and the electron beam will form a spot on the screen at the far end of the tube. As the accelerating voltage approaches 2000 V, diffraction rings concentric with the beam spot should form on the end of the tube. The system is now operational and as long as the carbon target does not glow, there is not too much current in the tube.

4. At an accelerating voltage of 2000 V, measure the diameters for each of the two rings which appears. The measurements should be from inner edge to inner edge. Repeat this procedure for 3000 V, 4000 V, and the highest voltage you can reach with the value not to exceed 5000 V. Refer to Figure 1 and determine \( \theta \) for each case.

5. Calculate the wavelengths of the electron for each voltage using Equation 2. Find the average wavelength for each accelerating voltage. These are your “measured” wavelengths.

6. Calculate the wavelength as predicted by the de Broglie relationship, Equation 1, for each voltage. These are your “expected” wavelengths, expected if the de Broglie relationship is true.

7. Compare the measured wavelength with the expected wavelength for each accelerating voltage. Do this by finding the percent difference for each voltage and then find the average percent difference. Are the results (measured as compared to predicted) in agreement to the number of significant figures obtainable in this experiment? Comment.
\[ r = \text{radius of the spherical tube, to be measured using the Cathometer traveling telescope} \]

To determine \( \theta \), first determine \( \psi \).

\[ y = r \sin \psi \]
\[ y = r \sin (s/r). \]

Then use the sagitta formula (which you should derive)

\[ X = \frac{y^2}{2r} \]

Then, \( \tan \theta = \frac{y}{L-X} \)

---

**Reference Matter**

[From Modern Physics, Sproul and Phillips, Wiley Pub, co., 1980 (p.118-121)]

3-9 **ELECTRON DIFFRACTION**

In this section we study experiments that show that electrons have the properties of waves. Classical physics considers electrons as point particles; the motion of an electron in electric and magnetic fields in the laboratory certainly agrees with the predictions of classical mechanics for the motion of a point charge. Only when experiments were performed that involved the interaction of electrons and atoms did it become apparent that classical mechanics was inadequate. In the crucial experiments performed by Davisson and Germer, a beam of monoenergetic electrons struck a nickel single crystal target, and the current of electrons reflected from the target was studied as a function of incident energy, emergent angle, and orientation of the crystal. This experiment showed that electrons are diffracted like waves when interacting with the crystal.

The Davisson-Germer experiment is illustrated in Fig. 3-31. The electron gun, target, and detector are all enclosed in an evacuated tube. The detector can be rotated so that \( \psi \) takes on different values. Classically, we should expect the electrons to be scattered by the nickel crystal, and some of them to enter the detector. The detector current may vary with \( \psi \) and the accelerating voltage \( V \), but we do not expect a very sensitive or striking dependence on either parameter. Electrons of any kinetic energy \( K \) should be deflected into all angles. (Many of them will lose a large fraction of their energy in the scattering process, but they will not be collected since the detector is only a few volts positive with respect to the cathode, and any appreciable loss of energy will prevent an electron from arriving at the detector).

Some of the results of this experiment are shown in Fig. 3-32. Superimposed on the (expected) background scattering is a peak in the current of reflected electrons centered on \( K = 54 \text{ eV} \) and \( \psi = 50^\circ \), which is quite unexpected on the basis of classical theory. This reflection is clearly selective in both angle and energy; we shall show that both forms of selectivity are exactly what would be expected if electrons have the properties of waves.
Before this experiment had been performed, de Broglie had proposed the hypothesis that electrons should be diffracted as if they had a wavelength

\[ \lambda = \frac{h}{mv} = \frac{h}{(2mK)^{1/2}} \quad (3-18) \]

For \( K = 54 \text{ eV} \) we calculate from eq. 3-18 that \( \lambda = 1.67 \times 10^{-10} \text{m} \) or 1.67 A. This is the same order of magnitude as the spacing between atoms in the nickel crystal, and we therefore attempt to understand the selective reflection as the result of diffraction of waves of this wavelength from the three-dimensional array of nickel atoms.

This diffraction is complicated by the fact that low-energy electrons (unlike X rays) are strongly scattered by atoms and hence do not penetrate more than a few atomic layers into the crystal. We consider only the surface layer of atoms, which are the major participants in the reflection and are shown in Fig. 3-31(b). Rows of these atoms separated by a distance \( d \) diffract like the mirror diffraction gratings commonly used in practical spectrographs for visible light (but they are rarely described in textbooks, most of which illustrate only transmission gratings). Constructive interference of the waves scattered by different rows of atoms occurs when \( n \lambda = d \sin \psi \), where \( n \) is an integer.

Now \( d \) can be determined to be 2.15 A from X-ray measurements for this particular orientation of the nickel crystal, and therefore \( \lambda = 2.15 \times \sin 50^\circ = 1.65 \text{ A} \), in excellent agreement with de Broglie's hypothesis. [We have let \( n = 1 \) since, if \( n = 2 \) or more, other reflections (not observed) would have appeared for \( \psi = 23^\circ \) or less.]

Agreement such as this was obtained by Davisson and Germer for widely different values of \( \lambda, n, d, \) and \( K \). In every experiment, the electrons were found to behave like waves.

---

Figure 3-32
Detector current as a function of angle and electron kinetic energy in the Davisson-Germer experiment.

Figure 3-31
(a) The Davisson-Germer experiment. Electrons encounter a retarding field inside the detector so that the measured current consists of only those electrons that have been scattered with negligible loss of energy.
(b) Interference among partial reflections from surface atoms.
with the wavelength given by eq. 3-18. These experiments prove that electrons are diffracted by a grating of atomic-size spacing just as waves are diffracted.

The selectivity in angle and in K exhibited in Fig. 3-32 resembles a diffraction pattern from a grating of only a few lines, rather than from thousands of lines or atom planes as is common in visible light or X-ray diffraction experiments. Surface imperfections restrict the interference shown in Fig. 3-31 to a small number of rows of atoms.

Electron diffraction experiments and apparatus are now common. The usual technique, quite similar to the powder diffraction method with X rays, was discovered independently by G. P. Thomson almost simultaneously with the Davisson-Germer experiment. Electrons are accelerated through a potential difference of up to 500,000 V and strike a sample. The diffraction pattern is observed on a photographic film and as can be seen in Fig. 3-33 exhibits much sharper lines than the diffraction shown in Fig. 3-32, since hundreds of atomic planes participate in the diffraction of these transmitted electrons. Applications of low-energy electron diffraction are described in Sec. 9-8.

Figure 3-33
The diffraction pattern of 200 keV electrons scattered from a thin gold foil, taken with the Cambridge University High Voltage Electron Microscope
Manufacturer’s Instructions

ELECTRON DIFFRACTION TUBE TEL 555

The Electron Diffraction Tube TEL 555* has been improved to give greater protection of the diffracting graphitised-carbon layer and to provide a wider range of voltage (see Nuffield Advanced Science: Physics Unit 10 “Waves, Particles and Atoms” p.52).

READ THESE NOTES BEFORE USING THE TUBE!

Connect e.h.t. negative to the 2mm diameter socket only: In the previous design, e.h.t. negative was connected to the heater; this must not now be done otherwise the diffracting layer could be damaged.

Automatic Biassing

The construction of the gun has been modified to provide better control of the emitted electron current. This is effected by “automatically biassing” the cathode can that surrounds the cathode by arranging for the total emitted current to pass through a resistor connected between cathodes and can in such a way that the latter is kept negative with respect to the cathode. Increase in current makes the can more negative so reducing the emitted current and, incidentally, improving the focusing. The cathode can is connected to the 2mm diameter socket in the base cap; a free plug is supplied with each tube.

External Biassing

Further control of the cathode ray current can be achieved by connecting the -ve terminal of the heater (which is connected internally to the cathode) and the 2mm diameter socket to an external 0-50V source. By increasing the negative bias at the latter terminal, improved focusing allows the diffraction pattern to be seen at lower e.h.t.

Negligible current is required and the beam can be “cut off” at about -40V.

Operational Parameters

Anode Current - 0.2 ± 0.05mA for $V_A = 5$ kV
Heater Voltage - 6.0 ± 1 Volt a.c

Because the anode current is low, higher voltages can be achieved thus permitting wider range of experimental points giving greater precision.

As a safeguard, a meter should be included in the anode circuit at all times.
Every care has been taken in selecting the biasing resistor, R, individually, but the nickel grid supporting the diffracting layer of carbon in the exit-anode of the gun should be inspected from time to time to check that it is not overheating. If so, the heater voltage should be reduced slightly. In general, the operation should be satisfactory and independent of the heater voltage over the range given above.
ELECTRON DIFFRACTION TUBE, TEL 555

ELECTRON DIFFRACTION TUBE, TEL 555 & OPTICAL ANALOGUE, TEL 555a

The Optical Analogue, TEL 555a, comprises an aluminum disc mounted on a hollow shaft which rotates in a ball-race in a plastics holder. The holder can be mounted in the back of the jaws of the Universal Stand. Located in the bore of the shaft is a rectilinear, 500-mesh grid. Supplied with the Analogue are two color filters and an aperture for use with a 35 mm projector.

The Electron Diffraction Tube, TEL 555, comprises a ‘gun’ which emits a converging narrow beam of cathode rays within an evacuated clear gins bulb on the surface of which is deposited a luminescent screen. The cathode rays pass through a thin layer of graphiticised carbon supported on a fine mesh grid in the exit apertu re of the ‘gun’ and are diffracted into two rings corresponding to separations of the carbon atoms of 1.23 and 2.13 angstroms. The source of the cathode rays is an indirectly-heated oxide-coated cathode, the heater of which is connected to 4 mm sockets in a plastics cap at the end of the neck; connection to the anode of the ‘gun’ is by a 4 plug mounted on the side of the neck.

The tube can be mounted on the Universal Stand, TEL 501. A rotatable magnet which can be clipped onto the neck of the tube to provide a means of deflecting the cathode rays within the gun to give the best diffraction pattern.

Specification:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filament voltage</td>
<td>Normal 6.3 V a.c. / d.c. ; max. 9.0V a.c. / d.c.</td>
</tr>
<tr>
<td>Anode voltage</td>
<td>3,500 – 5,000V d.c</td>
</tr>
<tr>
<td>Anode current</td>
<td>0.2 – 0.4 mA</td>
</tr>
</tbody>
</table>

Recommended Experiments:

Experiments with the Maltese Cross Tube, TEL 523, demonstrate that cathode rays exhibit some properties similar to those of light and other properties consistent with electrically charged particles. It was suggested by de Broglie in 1926 that particles could have wave properties where the wavelength, $\lambda$, is inversely proportional to momentum, $\lambda = h / mv$, $h = \text{Planck’s constant}$.

The Teltron Series ‘A’ Experiments confirm that electrons obey the laws of motion and lead to a measure of the specific charge $e / m$. The Millikan experiment establishes the discrete nature of the electron, gives a measure of charge $e$ and thereby an evaluation of its mass $m$. Sufficient information is thus available to test de Broglie’s hypothesis.

The possibility of diffraction:

A calculation using de Broglie’s equation shows that electrons accelerated through a p.d. of 4 kV have a wavelength of about 0.2 angstroms. Interference and diffraction effects, as studied in physical optics, demonstrate the existence of waves. For a simple ruled grating,
the condition for diffraction is \( \lambda = d \sin \theta \) or for small angles \( \theta = \lambda / d \), do being the spacing of the grating.

The best man-made gratings are ruled at 40,000 lines/inch and with a wavelength of 0.2A, \( \theta \) will be one second of arc or only \( 1/2 \) at 10 m from the grating. If electron diffraction is to be observed in a Teltron tube of 13.5 cm diameter, the spacing between ‘rulings’ to produce the first order at 1.35 cms from zero, (i.e. \( \sin \theta = 0.1 \)), must be 2.0A.

It was von Laue who suggested, in connection with x-ray studies, that if fine gratings could not be made by man because of the structure of matter, then perhaps the structure of matter itself could be used as a grating. Bragg, using the cubic system of NaCl, first calculated the interatomic spacings and showed them to be of the right order for x-rays.

A similar calculation using carbon assuming that its atoms form a simple cubic system, can be made, viz: 12 gms of carbon contain \( 6 \times 10^{23} \) atoms (Avogadro’s No.); since the density of carbon is about 2 gms/cm³, 1 cm³ contains \( 10^{23} \) atoms so that adjacent carbon atoms will be about \( \sqrt[3]{10} \) or a little over 0.2 A apart. In other words, carbon should provide a grating at the correct spacing for the experiment. The nature of the effect to be observed however is not evident from these calculations.

**Experiment 22 (Series ‘A’) Optical analogue of electron diffraction.**

The nature of the diffraction effect from the carbon “grating” can be investigated optically. The rectilinear grid corresponds to a section through the assumed cubic arrangement of carbon atoms. Set up the optical analogue as in Figure 1 and focus the spot produced by the slide onto a screen and then interpose the analogue. Alternatively, view a point source of white light directly through the analogue.

![Figure 1](image)

A colored “cross” pattern is observed indicating that the grid is acting as two line gratings perpendicular to each other. This symmetrical pattern would therefore be observed if the carbon atoms are uniformly arranged. If, however, a more or less random arrangement of equally spaced atoms exists, then a different pattern should be observed. Such a random arrangement can be simulated by rotating the grid rapidly, when a ring pattern is observed.

The dependence of the diffraction pattern on wavelength can be tested by viewing in red and green light, when it is seen that the ring diameter decreases significantly with decrease in wavelength (red to green).
Experiment 23 (Series ‘A’) Demonstration of Electron Diffraction.

Connect the tube, TEL 555, into the circuit shown in Figure 2, and switch on the heater supply and allow about one minute for it to stabilise. Adjust the E.H.T. setting to 4 kV and switch on.

Two prominent rings about a central spot are observed, the diameter of the inner ring being in fair agreement with the calculated value.

Variation of the anode voltage causes a change in ring diameter, a decrease in voltage resulting in an increase in diameter. This is in accord with de Broglie’s suggestion that wavelength increases with decrease in momentum.

Although conclusive evidence of the particulate nature of the electron has been previously obtained, this demonstration which closes resembles the optical one reveals the dual nature of the electron.

Experiment 24 (Series ‘A’) Variation of Electron Wavelength with Anode Voltage.

Use the circuit in Figure 2 and measure (in a darkened room) the diameter of the rings with different anode voltages $V_a$ and tabulate results.

An expression for the momentum of electrons can be derived from the ‘gun’ equation 14.3, $eV_a = \frac{1}{2} mv^2$ which substituted in de Broglie’s equation gives

$$\lambda = \frac{h}{\sqrt{2emV_a}} = \sqrt{\frac{150}{V_a}} \text{ angstroms}$$

24.1

If the beam travels a distance $L$ after diffraction through a small angle $\theta$, the diameter of the resulting ring is:

$$D = 2L \theta$$

24.2

From the diffraction equation, $\lambda = d \theta$ for small angles.
Substituting in equation 24.2 it is seen that the ring diameter is proportional to wavelength

$$\lambda = \frac{Dd}{2L}$$  \hspace{1cm} 24.3

Finally, equating equations 24.1 and 24.3 and rearranging, the ring diameter is found to be inversely proportional to the square root of the anode voltage

$$D = \frac{2L \sqrt{150}}{d \sqrt{V_a}}$$  \hspace{1cm} 24.4

To verify the theory, plot a graph of ring diameter $V_a^{-1/2}$,

(a) the straight lines obtained for the two circles verify the theory and substantiate de Broglie’s hypothesis.
(b) from the gradients, the spacing, d, for the two sets of diffracting planes can be calculated.
(c) the ratio of the spacings are found to be $\sqrt{3} : 1$ suggesting that the arrangement of carbon atoms is more likely to be hexagonal than cubic.

**Typical Results:**

<table>
<thead>
<tr>
<th>$V_a$ (KV)</th>
<th>2.5</th>
<th>4.0</th>
<th>6.0</th>
<th>6.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>D = Outer ring</td>
<td>50</td>
<td>43</td>
<td>39</td>
<td>36</td>
</tr>
<tr>
<td>D = Inner ring</td>
<td>29</td>
<td>25</td>
<td>24</td>
<td>21</td>
</tr>
</tbody>
</table>

$L = 13.5$ cm

d_{inner} = 1.20 \text{ A}

$(d_{11} = 1.23 \text{ A})$

d_{outer} = 2.06 \text{ A}

$(d_{10} = 2.17 \text{ A})$
APPENDIX A

GUIDELINES FOR FORM OF LABORATORY NOTEBOOK

1. Each of the 4 projects should be described in a laboratory notebook. The laboratory notebook should be spiral bound and contain no loose pages. You may staple or tape additional pages (computer generated data tables and graphs, for example) into the notebook. Neatness is very important. Each project should have a title page containing the experiment name and number, and the name of your laboratory partner(s).

2. A brief description of procedure should accompany all presentations of data. Stand alone data tables are never easy to interpret.

3. A presentation of relevant theory should accompany all calculations. Calculations without theory are usually difficult to follow. Do not show simple arithmetic. Do indicate how all calculations are done when stating results.

4. All tables and graphs should be numbered and have a descriptive title. All should be accompanied by statements specifying how their content is related to the particular project. A verbal analysis of the significance of graphs and tables should always be presented. Graphs and tables do not stand alone.

5. Each experiment should have a project summary. In this summary you should: (1) recap significant aspects of the project, (2) present the results and an analysis of the results that makes reference to relevant theory, data, tables, and graphs, and (3) state conclusions drawn from this analysis.

6. Some experiments specify that certain derivations of theory be performed as a part of the project.
APPENDIX B

ORGANIZATION OF THE LABORATORY REPORT

Although the organization and style of a scientific report is not bound by any fixed rules, there are some characteristics that are common to virtually all of them as you will see when you look over papers published in The American Journal of Physics. All scientific papers exhibit a title, the name(s) of the author(s), and the date of publication. All scientific papers begin with an abstract. The abstract is followed with the body of the paper. The body of the paper almost always begins with an introduction. The introduction prepares the reader for what is to follow. A discussion of relevant theory is included in the body text, either as part of the introduction or in a separate section. Relevant experimental apparatus is described and illustrated with clearly drawn diagrams when discussing experimental procedures. Experimental results are presented and analyzed. The final part of the body of a paper is the summary. Each of these components are described in more detail in the following as they relate specifically to this laboratory course.

I. Title Page
The first page of your report should be the title page. It should display the title of the experiment, the date it is submitted, your name, and your lab partner's name, if you have one.

II. Abstract
The abstract should be presented on the second page of the report. Although the abstract is presented before the body of the report, it should actually be written only after the remainder of the report has been completed. The abstract should be no more than 100 - 150 words in length and should be a complete statement of all important aspects of the work. A good abstract always includes important numerical results. The abstract should not be confused with the introduction and/or procedure, although it may contain certain elements of both. It should also not be confused with the conclusion. The writing of a good abstract requires considerable practice. The abstract contains the whole story of the paper, without details, and, if properly written, will stand as a complete and comprehensible unit for the reader who does not want to read the entire paper. In other words, the reader of an abstract should, by reading nothing but the abstract, be able to ascertain what you did, the results obtained, and the relevance of those results. Two examples of properly written abstracts are presented on the next page. Study them for style.

III. Body of the Report
The various parts of the body of the report are discussed next. Actual subdivision of the report and/or the order in which they are presented may vary. Some parts may be combined. For example, the introduction could be combined with the theory. Or, the experimental procedure could be combined with the presentation of results. The nature of the experiment itself will usually determine this. However, regardless of the order in
which the items discussed below are presented and/or combined, they will, in almost all cases, need to be a part of the report. The report should be written at a level appropriate for a reader who has a physics background similar to yours, but who may not be immediately with the details of the particular experiment on which you are reporting. It should be written using smoothly flowing prose, much in the same style as a novel.

1. Introduction
The introduction should make clear what the experiment is about and why the experiment is important. Its purpose is to prepare the reader for what will follow. The introduction is often a good place to make the reader aware of any background needed to understand the significance of the particular work being reported.

2. Theory
A theory related to the work done should be presented. Usually this will be in the form of a summary unless the purpose of the paper is to present the theory itself. Theory not specifically developed in the report should be referenced as to origin. All symbols should be defined. Do not present trivial theory that can be considered common knowledge. Detailed, complicated, and/or lengthy theoretical presentations are sometimes best put in an appendix. This is especially true if presentation of the theory interrupts the main train of thought. It is important that the report flow smoothly. Incorporating equations, tables, diagrams, and graphs into the text is sometimes difficult for the beginning scientific writer. All equations should be couched in complete sentences that are properly punctuated. All equations to which you will later refer should be numbered and referenced to by that number when used later in the text.

3. Description of the Experiment
All papers reporting the results of an experimental investigation should contain a description of the experiment which includes both a discussion of the procedure and a description of the apparatus. This section, like all others in the body of the paper, should be written using smoothly flowing prose. Unlike procedures given in laboratory manuals, which are written using a style that tells the experimenter what to do, the writer of a scientific paper should describe the experiment using a style that tells the reader what has been done. The description of the experiment should not be unnecessarily detailed, but it needs to be complete enough for the reader to fully understand what was done. Diagrams of the apparatus and an explanation describing how the apparatus was used should be a part of this section.
In many cases the writer finds it convenient to present experimental results at the same time the experiment is being described. This is a key part of the report. Conclusions are based upon these results so it is very important the reader understand, not only what was done, but the results obtained. Results are best presented using graphs and tables. Just as with equations, graphs and tables should be incorporated into the text. All graphs and tables should be given both a descriptive title and a number. The writer should refer to specific graphs and tables by these numbers whenever they are presented and/or discussed in the text. Failure to properly reference a graph or table in the text is always inappropriate.
As a rule, neither calculation details nor sample calculations are included in the report. An exception to the rule might occur if the primary purpose of the paper was to show the reader how to do a particular calculation. Results of calculations are included. The writer
should present just enough detail when presenting the results of calculations to allow the reader to reproduce each calculation. This means that all data and measurements needed to perform each calculation must be clearly presented in the paper.

4. Discussion of Results and Conclusions
This section of the paper is the one for which the earlier portions have been preparing the reader. Here you critically combine the results with theory. When making an assertion be sure to give both numerical results and specific theoretical relations supporting the assertion. Discuss discrepancies, if any, between results and theoretical expectations. Specify the size of any discrepancy. When comparing X and Y, don't just say X is greater than Y. Rather, say X is 3 times larger than Y. If you think X agrees with Y, don't just say X agrees with Y. Rather, say X, which has a value of $1.4 \pm 0.1$, agrees with Y which has a value $1.5 \pm 0.2$. If you have not already done so, this is a good place to compare the actual experimental conditions with those actually present. When doing this don't make vague unsubstantiated statements. Be specific. Make estimates, if possible, of the size of the error resulting from neglecting certain experimental conditions in the theory.

The final paragraph(s) should be a summary. This summary is the final statement of the significance of the work.

5. Appendices
Two items are sometimes referred to an appendix. They are as follows.

a. Any discussion of a small point which interrupts the train of thought in the body of the report is put in an appendix.

b. Long and involved mathematical treatments.

All material in an appendix should be referenced in the body of the report. The appendix should be completely understandable without the reader having to refer to the body of the report. In addition, the text should be completely understandable without the reader having to refer to an appendix. Each should stand alone.

t these derivations in an appendix following the conclusion.