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QUANTUM PHYSICS LAB MANUAL (PHYS 284)

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Introduction

This is the introduction about the course and these labs.

Calculating uncertainties

Concepts covered in this lab

- Statistical uncertainties.
- Systematic uncertainties.
- Combining uncertainties.
- Plotting and graphing.

Introduction

Based on the class lecture and the appendix on experimental error you should now be familiar with the concepts of:

- The mean or average $\langle x \rangle$.
- The standard deviation σ.
- The standard deviaiton of the mean σ_{mean}.
- How to quote a measurement and the associated uncertainty.
- Methods for estimating the uncertainty.
- How to combine uncertainties.
- What is the difference between the statistical and systematic uncertainties.

Goal of this lab

To learn error analysis techniques, graphing techniques and to apply these to find the statistics of the weights of pennies. There is no lab report for this lab.

The experiment

Procedure

Part A

Count out 100 pennies for the measurement. Using the provided scale, weigh each of the pennies and record the values. You will find

that the pennies fall into two groups, new pennies, which weigh around 2.5 g, and older pennies which weight around 3.0 g. Only keep the data for the new pennies. Calculate the following quantities from the data a) the mean weight, b) the standard deviation (error) of the mean weight c) the standard deviation of the mean of the weights. Now use the provided Python code to plot a histogram of the distribution of weights.

Part B

Weigh the pennies a second time, but this time weigh them in 10 groups of ten pennies each. Again calculate the average, standard deviation, and standard deviation of the mean of the weights. Based on these measurements estimate the mean weight of a single penny and the error in this weight. Compare this result to what you obtained in part A.

Extra Credit

There is no report for this lab, but if you like you can submit answers to the following questions for extra credit.

1. Do you think the variation in weight is due to the scale or due to the variation between pennies. Is there any way you can think of to distinguish between these two possibilities?

2. What do you think are the causes for the variations you see? Do you think these errors are mostly systematic or random? When you did the lab, did you make any mistakes, which required you to throw out data and retake it? If so, what were they? Do you think there were less carefull groups which might have counted those mistakes as experimental error? If so, how might you detect such mistakes?

3. Suppose that you were trying to count pennies by weighing them in mass. Assuming you only had modern pennies (approximately 2.50 g, not 3.20 g), what is the most pennies you could weigh before you would have a significant chance of miscounting them by their weight? Explain your reasoning.

4. If there are no systematic errors, then histogram of the penny weight should ideally follow a bell curve, or gaussian, given by

$$N = N_{tot} \frac{1}{2\pi\sigma^2} e^{-(x-\langle x\rangle)^2/2\sigma^2} \Delta x$$

Here N is the number in a histogram bin of width Δx, N_{tot} is the total number of pennies measured, $\langle x\rangle$ is the mean and σ is the

standard deviation. Plot a graph of the appropriate gaussian on top of your histogram.

Problems

Try to do the following exercises using the python computer code. You should try these while in lab so that you can ask the instructor for help. These will not be graded.

1. You have measured the length of a piece of paper a number of seperate times. The values are 27.94, 27.96, 27.99, 27.97, 28.00, 27.93,27.96, 27.98. Find the mean, the standard deviation, and the standard deviation of the mean of these values.

2. Suppose you measured several of lengths and their errors. $l_1 = 23.5 \pm 0.1$cm $l_2 = 17.8 \pm 0.2$cm 93.9 ± 0.2 cm. Find the sum of these three lengths and the error in the value of the sum.

3. The gravitation attraction between two masses is given by the formula

$$F = \frac{Gm_1m_2}{r^2}.$$

   Calculate F and ΔF given $G = 6.67384(80) \times 10^{-11} m^3 kg^{-1} s^{-2}$, $m_1 = 9.7 \pm 0.2$kg, $m_2 = 9.4 \pm 0.2$kg and $r = 0.641 \pm 0.009$m.

4. The index of refraction of glass can be obtained from the formula $n_g = n_{air} \sin(\theta_{air}) / \sin(\theta_g)$. Find n_g and Δn_g using $n_{air} = 1.000$, $\theta_{air} = 61 \pm 2^\circ$ and $\theta_g = 31 \pm 1^\circ$.

5. Consider a mass under uniform acceleration. The velocity will be a linear function of time. From a straight line fit to the velocity vs. time, you can then obtain the acceleration. Perform a linear fit to the velocity data given below using the supplied python code. Find the acceleration and its uncertainty. You may assume that the error is the same for every velocity measurement and is given by $\Delta V = 0.01$m/s.

6. The resistance of a tungsten wire is proportional to the absolute temperature in Kelvin. The table below gives R vs. T data for a flashlight bulb. The extrapolated temperature at $R = 0$ should then be absolute zero. Fit the data to a straight line graph of T vs. R and find the predicted value of absolute zero from m and b. Also find the uncertainty in this value using error propagation. You may assume that $\Delta T = 100C$.

Velocity (m/s)	Time (s)
-.55	1.0
-.19	2.0
-.09	3.0
.01	4.0
.36	5.0
.56	6.0
.65	7.0
.85	8.0
1.17	9.0

Table 1: Acceleration Measurement of a Mass

R (Ohms)	Color	T (C)
15.4	Bright Red	900
18.7	Yellowish-red	1100
20.6	Incipient white	1300
23.0	White	1450

Table 2: Acceleration Measurement of a Mass

Diffraction gratings and spectrometers.

Physics introduction

Physics concepts covered in this lab

- The wave nature of light (see Appendix).

- Diffraction gratings (see Appendix).

- Quantization of energy in atomic spectra (see Appendix).

Pre-lab questions about the physics

Discussion question: For the examples in the double-slit experiment, we were often given numbers like $d = 5 \times 10^{-4} m$. For a diffraction grating with 600 lines/mm, what is d?

The experiment

Introduction

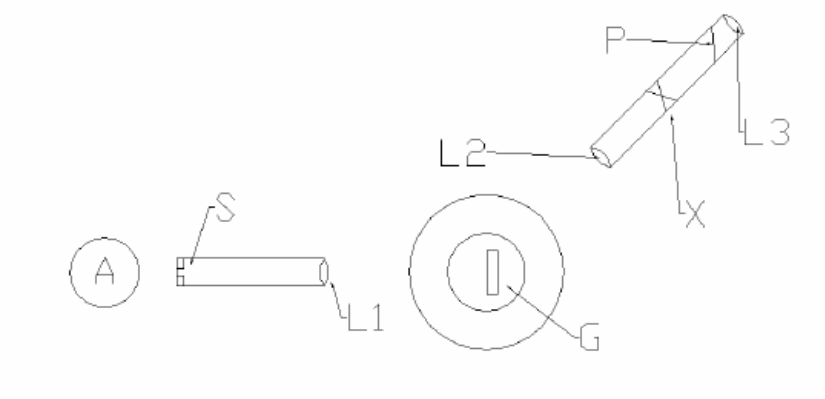


Figure 1: Schematic of experimental setup.

Introduction

In this lab you will use a diffraction grating spectrometer to measure the spectra of sodium vapor. Fig. 1 provides a schematic of the spectrometer. Light generated by a lamp A enters the spectrometer through slit S. Lens L1 collimates the light from the slit onto the grating G. After passing through the grating the light diffracts at angle

$$\theta = \arcsin \frac{\lambda}{d}$$

. Here d is the line spacing of the grating (1/600 mm) and λ the wavelength of the light.

Lens L2, focuses the light from the grating to an image point near the focus of the eyepiece L3. Lens L3 magnifies the image for your eye. Halfway down the barrel which holds L2 and L3 is a cross hair, X. This is used for centering the diffraction lines. There is also a small glass plate P, just in front of the eyepiece that can be used to direct an external light to illuminate the cross hair.

Alignment

Set up the spectrometer on a circular wooden stand and one of the Sodium lamps on one of the thinner square pieces of wood. The slit of the spectrometer should fit neatly into the aperture on the lamp.

Initial alignment

1. Set the slit opening to 0.25 mm.
2. Place a 600 line/mm diffraction grating at the center of the spectrometer. Avoid touching the face of the grating or any of the lenses. Use the release knob on the base of the spectrometer to coarsely align the face of the spectrometer parallel to the collimating lens, L1.
3. Check that the three thumbscrews on the grating mount are adjusted so that the grating is perpendicular to the ground.

Fine alignment

1. Sight along the viewing barrel directly at the slit. Adjust the vertical height of the collimating barrel with the thumbscrew to center the line vertically in the eyepiece.
2. Swing the viewing barrel clockwise until you have the spectrometer centered on the first bright yellow diffraction line. The vertical height of the slit image has probably moved. Adjust the three thumbscrews that hold the grating until the image of the slit is again centered.
3. Swing the viewing barrel counterclockwise to the symmetrically located diffraction line at the other side of the center. Check that the slit remains centered vertically on the image of the line.

Measurement of the Sodium Spectra

1. Swing the spectrometer arm clockwise to the position of the first order yellow line (this line is call the sodium "D" line). Find the exact position of the center of the line using the cross hair. For fine adjustment of the spectrometer you can lock the detector arm with the thumbscrew and use the fine adjust screw. Read the position of the center of the peak using the magnifying glass over the dial. There is a vernier scale above the gauge that will allow you to read the dial to within 1 minute of arc (1/60 of a degree).
2. Swing the spectrometer to measure the position of the "D" line at negative angle and measure the position.
3. Even after careful alignment, the diffraction grating will not be exactly parallel to the incident light. One way to overcome this problem is to calculate the wavelength as

$$\lambda = d\frac{\sin(\theta_+) + \sin(\theta_-)}{2} \tag{1}$$

By calculating the average of the sines of the angle you will remove most of the error associated with the light not being incident completely perpendicular to the grating. If you see a significant difference between + and - then you should make a small adjustment to the grating angle in order to make the angles come out closer to even.

4. Each lab partner should now measure both the first order ($d \sin\theta = \lambda$) and second order ($d \sin\theta = 2\lambda$) diffraction peaks for the yellow sodium line. Estimate the uncertainty in your value for the wavelength. You can determine the uncertainty from the variation in your results. If your measurements are the same, then you should try to determine the positions with more precision by interpolating between numbers on the dial. Describe carefully in your notebook how you calculate the uncertainty.

Measure the other spectral lines of sodium

1. Measure the angles corresponding to the other colored lines from Sodium. Measure both orders and both positive and negative angles.

2. Combine all your measurements with your lab partners and estimate the uncertainty in the wavelengths of the lines.

3. Estimate the relative intensity of the lines. (E.g. Very bright, bright, weak, very weak).

Measure the splitting of the sodium D lines

1. The D line is a doublet with wavelengths 589.6 nm and 589.0 nm. Adjust the incident slit as narrow as you can, while still getting a single, well- defined line when viewed at =0 through the eyepiece.

2. Go to the first- and second-order peaks for the yellow line and measure the splitting. Make careful notes in your notebook describing what steps you take to get the most accurate measurement of the line splitting that you can.

3. Now go on and measure the splittings of the other colored lines.

Measure the spectrum of atomic hydrogen

1. There is one hydrogen lamp source available for the laboratory. When the lamp is available, use this to measure the wavelengths of the lines from hydrogen.

Diffraction Grating Pre-Lab Questions

1. Explain why the light has to be collimated before hitting the grating.
2. The zero-angle of the spectrometer is defined by the position where the viewing telescope directly images the source slit. For a perfectly aligned spectrometer, the normal to the surface of the diffraction grating will be exactly aligned to zero. Suppose that, due to mis-alignment, the face of the diffraction grating is tilted by an angle, α. Consider a diffraction peak which would normally appear at angles $+\theta$ and $-\theta$, (depending on which side of the zero angle you are looking). Calculate which angles the peak appears when the grating is tilted by α.
3. In order to correct for a misalignment of the diffraction grating you measure the position of a peak on either side of the spectrometer. Derive formula 1 for the wavelength terms of the two measured angles θ_- and θ_+ which you find when the grating is tilted by α.

Diffraction Grating Lab Report Guidelines

1. Introduction
   - Briefly describe what the lab is about.
2. Procedure
   - Discuss specifically how you aligned the spectrometer. Which steps were very easy and which steps required particular care?
   - Discuss what you had to do to measure your lines most accurately. What value of slit size did you choose? Why didn't you use a smaller or a wider size?
   - Discuss any special precautions you took. How did you align the cross hairs? Was it necessary to turn off the room lights. When did you need to use the fine adjustment screws? Did you ever have to
3. Other
   - Answer any questions you find throughout the lab procedure.

Michelson Interferometer

Physics introduction

Physics concepts covered in this lab

- The wave nature of light (see Appendix).

- The Michelson interferometer (see Appendix).

- Quantization of energy in atomic spectra (see Appendix).

Pre-lab questions about the physics

Discussion question: For the examples in the double-slit experiment, we were often given numbers like $d = 5 \times 10^{-4} m$. For a diffraction grating with 600 lines/mm, what is d?

The experiment

The purpose of this lab is to see interference in action, to understand the principles of a basic interferometer and to study the connection between a path-length difference and a phase shift. In the first part of the lab a Michaelson interferometer is calibrated using a sodium light source. In the second part of the lab this calibration is used to determine the wavelength of a mercury lamp.

Introduction

A Michaelson interferometer (Fig.2) splits light into two waves that travel different paths and are then recombined. One of the paths is fixed length and the other path is of variable length (see Fig.2). At the point (M) where the beams split, each is in phase with the other. When the beams recombine at the detector they may no longer be in phase since each has traversed a different path. The phase difference can be adjusted by changing the position of the movable mirror (A). The phase difference is given by

$$\phi = 2\pi \frac{(a_x 1 - a_x 2)}{\lambda} \tag{2}$$

Here x_1 and x_2 are the path lengths traveled along each of the two arms of the interferometer. If the path length difference ($\Delta x = x_1 - x_2$) equals an integer number of wavelengths then the waves recombine in-phase and the intensity will be a maximum. For Δx a half-integer number of wavelengths the intensity will be zero.

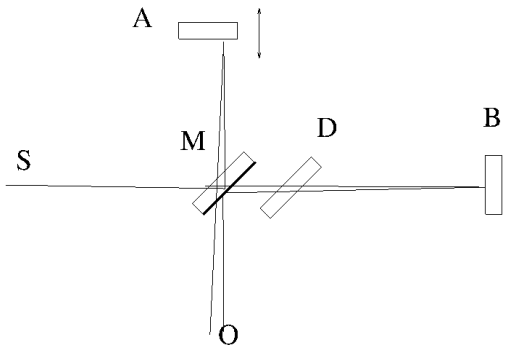


Figure 2: Schematic of Michaelson Interferometer.

The detailed operation of the interferometer is as follows. A light source, **S**, emits light which impinges upon a beam-splitter M. The beam-splitter is a half-silvered (lightly silvered on one surface) mirror. Half of the incident light is reflected towards the mirror **A**, and the other half proceeds towards the mirror **B**. Light impinging on these mirrors is reflected directly back towards the **M** position. When

this light reflected back from **B** encounters the beam-splitter, the light is partially passed towards **S** and partially reflected towards the observer **O**. Similarly; light reflected from **A** back towards **M** is partially reflected towards **S** and partially passed towards the observer. Object **D** is a glass plate as thick as the beam splitter inserted so that regardless of the path taken, the rays of light travel through the same total thickness of glass[1]. If the effective distance[2] from **M** to A and back differs by an integral number of wavelengths from the effective distance from **M** to **B** and back, then the observer measures constructive interference. Imagine that the mirror **A** is moved back a distance equal to $\lambda/4$. The light wave along that path has traveled $\lambda/2$ farther than the light moving on the fixed arm of the interferometer. With this motion, one would see a bright spot go to a dark spot, or a dark to a bright. If the mirror **A** continues to move back the observer will see dark/bright/dark cycle each time the mirror is moved back an additional $\lambda/2$. In order to perform interferometer experiment, the user controls the motion of one of the mirrors through a micrometer[3]. We designate the micrometer position as P. The micrometer pushes on a lever which moves the mirror. Because of the lever each 1m moved by the micrometer corresponds to a smaller motion $1\mu m/K$ of the mirror. The scaling constant, K, is approximately 5, but an accurate determination of K is required to calibrate the instrument. Suppose that advancing the micrometer by ΔP yields n interference minima. The path length difference, $\Delta x = 2\Delta P/K$, has then changed by n. We can summarize this as:

$$\lambda = \frac{\Delta x}{n} = \frac{2\Delta P}{nK} \tag{3}$$

[1] If there is too large a difference in the total pathlength, the two waves will lose coherence and will not create an interference pattern.

[2] We use effective distance here rather than physical distance. If a distance d is traveled in a medium with index of refraction n then the effective distance is $d_{\text{eff}} = nd$. This is because the wavelength is shorter by $1/n$ within the medium. In the present case, the glass is the only part of the apparatus where the effective distance is not the same as the physical distance.

[3] A micrometer is a mechanical tool with a fine screw thread that makes precise and reproducible positioning motions. It is so named because it is capable of moving in increments as small as a millionth of a meter, or 1 micron = 1μm.

Experimental Procedure

In the first half of the lab you measure the calibration constant K using a sodium vapor light source with known wavelength $\lambda == 589$ nm.

1. Turn on sodium (Na) light source. Allow it a few minutes to warm up. If the lines are not clearly visible, you will need to realign the tilt of mirror B. This is done by adjusting the two screws so that the image of the pencil lines on the ground glass plate line up with each other. If this is not clear, ask for help. Make a diagram in your notebook of how the apparatus is set up, including the sodium light source.

2. Set up a small table in your lab book. You will need columns for P_0, P_1, and n, the number of fringes passed. Do not forget to

explicitly include the units. Add a title that describes that you are using a sodium (Na) source.

3. Set the micrometer at about 4mm. Then turn the micrometer clockwise until the reading is 5.00mm. The initial reading is now $P_0 = 5.00$mm. In order to avoid backlash errors do not change the direction in which you are turning the micrometer screw[4].
4. Slowly turn the micrometer still clockwise while counting the fringes. After successfully counting 100 fringes ($n = 100$) read the micrometer setting [5]. This is P_1. If you lost count, then throw out the data, reset the micrometer, and start again.
5. Reset the micrometer backwards to 5.00 proceeding as in step 4.
6. Switch places, and let your partner count 100 fringes while slowly turning micrometer clockwise, noting the P_1 position of the micrometer.
7. Repeat this process for at least 4 measurements.
8. Calculate the calibration of interferometer K using Eqn. 3 and the average value for ΔP over the four measurements. Use the standard deviation of the mean of your measurements of ΔP for the uncertainty. (If all the ΔP are exactly the same then assume that the error in each measurement is exactly $\frac{1}{2}$ fringes, and combines errors appropriately. Note this result down clearly in your notebook and give the value with the proper number of significant digits.
9. Turn off the Sodium source and switch to the Mercury lamp. Allow it a few minutes to warm up and then repeat the steps above to determine the wavelength of the light from Eqn. 3, using the calibration constant obtained in the first part.
10. Combine the errors in K and ΔP to obtain the error in λ using error propagation as discussed in the appendix on error analysis. Report this final value with its uncertainty (and the correct number of significant digits) in your lab book.
11. Go to the other students in the class and get their final values for the wavelength of mercury and its uncertainty. Check to see if the values agree with each other to within the uncertainties calculated by each lab group. If your value does not agree with the rest of the classes values, go back and double check your work (or alternately convince the rest of the class to go back and double check their work).
12. Switch to the white light sources. Write down in your notebook what is needed in order to obtain an interference pattern with white light. Describe the interference pattern in your notebook.

[4] When you adjust the micrometer position you do not turn the micrometer screw in both directions because backlash can be a problem. When a gear (or screw thread acting like a worm gear) is turning in one direction, the mechanical coupling is pressed up against one side of the teeth. This works fine as long as the user continues to turn the gear in the same direction. Anytime that the gears reverse direction, is takes a little turning before the gears start to press up against the other side of the teeth.

[5] The overall measurement will have less error when performed over a larger total path difference. Thus, instead of measuring the small motion necessary to move a single fringe, the total mirror motion necessary to shift the fringes by many phase shifts will be measured.

Pre-lab questions

Please submit the answers to these questions to the instructor before beginning your lab.

1. When the mirror (**A**) is moved by a distance dx1 then the light in that arm of the spectrometer travels an extra distance $2dx_1$. Why is there a factor of two?
2. Why do you think the motion of mirror (**A**) is made using both a micrometer and a lever arm. Wouldn't just using a micrometer screw be easier?
3. Suppose that the silvering of the mirror did not equally split the light, but rather reflected 80% and transmitted 20%. How would this effect the interference pattern. (Think carefully about this one!)
4. A glass compensating plate as thick as the beam splitter is inserted so that regardless of the path taken, the rays of light travel through the same total thickness of glass. Why does this equalize the paths traveled?
5. It turns out that the compensating plate (**D**) is not needed when a laser is used instead of a gas discharge tube. Why do you think that is?

Michaelson Interferemeter Lab Report Guidelines

1. Introduction:
   (a) Describe what the interferometer is and what the experiment will measure about it.
   (b) Keep this brief. There is no need for more than one paragraph here.
2. Procedure:
   (a) Draw a schematic of the interferometer and label the parts.
   (b) If you employed any tricks to get better accuracy in counting fringes describe them.
   (c) Describe how you counted the fringes. Did you use a particular mark for reference?
   (d) Describe any special precautions. Did you have to worry about shaking the table? Were the interference fringes more or less visible at different times, and if so, what conditions yielded the best pattern.

(e) Describe what you needed to do to get good white light fringes.

3. Data and Analysis:

(a) Present you measurements from both the first and second parts in tabular form. (e.g. basically make a typeset copy of the tables from your lab notebook). Make sure to include units in the table, and to give a short description of the table directly underneath.

(b) Describe how you calculated the uncertainties. Give details about the propagation of your error analysis. Specify if you used a calculator or a computer program to do the error analysis. Make sure to give all numbers using the proper number of significant digits.

(c) Present a table comparing the results of different groups in the class.

(d) Describe, qualitatively, your white light interference results.

4. Conclusions:

(a) Compare your final result for the frequency of the Hg line with both the tabulated value and with the average of the class.

(b) Compare the deviation between you result and the tabulated result with the size of your calculated uncertainty based on error analysis. What does this imply about the accuracy of your experiment?

(c) Describe how you might improve the experiment.

Photoelectric effect

Concepts covered in this lab

- The particle nature of light.
- The photoelectric effect.

  http://phet.colorado.edu/en/simulation/photoelectric
  PASCO material available. Do we rewrite this?

e/m ratio of the electron

Concepts covered in this lab

- The electron.
- Force on an electric charge in an electric field.
- Force on an electric charge in a magnetic field.

Supporting materials

http://www.hscphysics.edu.au/resource/template.swf

Introduction

The purpose of this lab is to measure the charge-to-mass (e/m) ratio of the electron by measuring the radius of curvature of a mono-energetic beam of electrons placed in a uniform magnetic field. Consider an electron moving with velocity v perpendicular to a magnetic field of magnitude B . The radius of the electrons orbit will be

$$r = \frac{mv}{eB} \tag{4}$$

If the electron's velocity is created by accelerating it through a potential V then its kinetic energy can be written as

$$KE = eV \tag{5}$$

In this setup, Eqn. 4 can be rewritten as

$$r^2 = \frac{2V}{B^2}\frac{m}{e} \tag{6}$$

From Eqn. 6 it can be seen that if a graph of r^2 as a function of V is fit to a straight line then the slope will be $\frac{1}{B^2}\frac{m}{e}$, from which the electron charge to mass ratio can be extracted, for a fixed B.

Procedure

In addition to these instructions there is a second PDF file with details of the apparatus, some relevant equations and diagrams of how the tube is to be setup. The operation of the tube is as follows. The e/m apparatus creates a beam of electrons by heating a metal filament with a current until electrons have enough thermal energy to leave the metal. These electrons are then accelerated by a voltage between the cathode and anode of the tube, which determines their kinetic energy. The electron beam is made visible by the fluorescence of hydrogen gas within the tube. The radius of the electron's orbit can be measured using a caliper on the outside of the electron tube.

For the experiment you will initially set up a constant magnetic field using a 2 A current through the Helmholtz coils. You can then plot Eqn. 6 by measuring the radius of the electrons orbit for different values of the accelerating voltage. Fit the data to a straight line and extract the slope together with the uncertainty in the slope. Next, keeping the voltage fixed, vary the magnetic field and repeat the analysis.

Note that the supplemental notes from Leybold will tell you how to calculate B using the current through the Helmoltz coil, the radius of the coils, and the number of turns of the wire.

Notes of caution

The following is pulled directly from the "*Safety notes*" provided by the Leybold company.

Attention: The fine beam tube requires dangerous contact voltages up to 300 V for accelerating the electrons. Other voltages that are connected with this dangerous contact voltage also present a contact hazard. Dangerous contact voltages are thus present at the connection panel of the holder and at the Helmholtz coils when the fine beam tube is in operation.

- Connect the connection panel only via safety connecting leads.
- Always be sure to switch off all power supplies before connecting and altering the experiment setup.
- Do not switch on the power supplies until you have finished assembling the circuit.
- Do not touch the experiment setup, particularly the Helmholtz coils, during operation.

Danger of implosions: The fine beam tube is a evacuated glass vessel with thin walls.

- Do not subject the fine beam tube to mechanical stresses.
- Operate the fine beam tube only in the holder (555 581).
- Connect the 6-pole plug of the holder carefully to the glass base.
- Read the instruction sheet supplied with the fine beam tube.

Helmholtz coils may be charged with more than 2 A for short time only.

Prelab Questions

1. Use the Biot-Savart Law to calculate the field at the center of two Helmholtz coils. For a Helmholtz coil the vertical seperation between the two coils is equal to the radius of the coils[6].
2. Derive Equation 4.
3. Derive Equation 6.
4. Discuss why the Helmholtz coil is made of two coils symmetrically placed above and below the electron tube. Why should this be better than a single coil around the tube?

[6] Note that if you were to just look up "Helmholtz coil" on Wikipedia then that might give you the answer, but you won't learn as much.

Lab report guidelines

Introduction

1. Discuss the method by which e/m will be measured.
2. Introduce the basic equations

Procedure

1. Draw a circuit diagram of your setup.
2. Outline the general steps you used to take the data.
3. Discuss any special tricks you used to get accurate measurements of the radius.

Data and Analysis

1. Graph the data according to Eqn.6 and fit it to a straight line.
2. Make sure you have a reasonable estimate for the uncertainties on the data points.
3. Make sure to obtain both the slope and the uncertainty in the slope for both measurements.
4. Make sure to properly label the graph axes and data points.

Conclusions

1. Compare your value of e/m with the tabulated values.
2. The intercept of your lines should, in principle, be zero. If they are not, discuss what type of systematic errors would lead to a non-zero intercept.
3. Suggest the possible sources of error in the experiment.
4. Discuss whether varying the B field or the Voltage is more accurate.

Supplementary materials

Some other materials from Leybold on the Helmholtz coil and the operation of the experimental apparatus (P6131_E.pdf).

Frank-Hertz experiment

Concepts covered in this lab

- Atomic energy levels (See Appendix).

Brief theory overview

Photons are emitted and absorbed by atoms only when their energy is exactly equal to the difference in energy between two atomic states. Similarly, when a moving electron collides with an atom, the energy lost by the electron will also equal the difference between two states of the atom. If the electron does not have enough energy to excite a transition it will bounce off the atom with no energy loss [7].

[7] If energy is lost during a collision it is termed inelastic, if no energy is lost the collision is termed elastic.

In the Frank-Hertz experiment you will examine collisions between mercury atoms and electrons and measure the energy lost in inelastic collisions. This experiment is similar to the original one done by Frank and Hertz which won them the Nobel Prize in physics in 1925. In order to perform the experiment the following things are needed.

1. A means to produce a dilute gas of Hg atoms.
2. A means to produce a beam of electrons with a well defined energy.
3. A means to measure how much energy is lost from the beam of electrons.

The first requirement is met by putting a small drop of Hg into an evacuated tube. Since Hg has a very low vapor pressure there will be negligible gas in the tube at room temperature. By heating up the Hg in a temperature controlled oven, the vapor pressure of the gas can be adjusted so as to give an appropriate number of collisions between Hg and an electron beam. The source of electrons is obtained by putting a metal filament into the vacuum tube and running a current across it to heat the filament. As the filament heats up some electrons will have enough thermal energy to overcome the work function

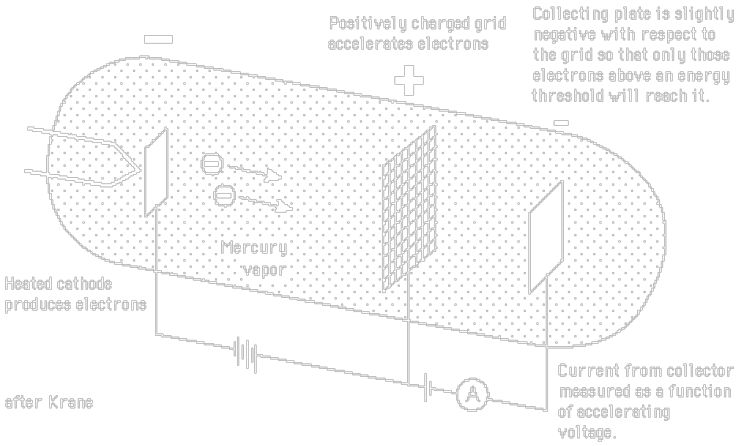


Figure 3: Schematic for Frank-Hertz apparatus. http://hyperphysics.phy-astr.gsu.edu/hbase/frhz.html

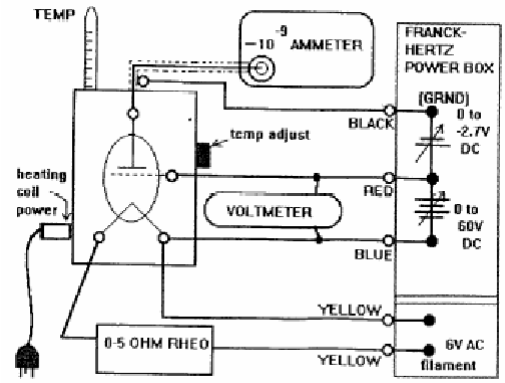


Figure 4: Circuit diagram for Frank-Hertz apparatus.

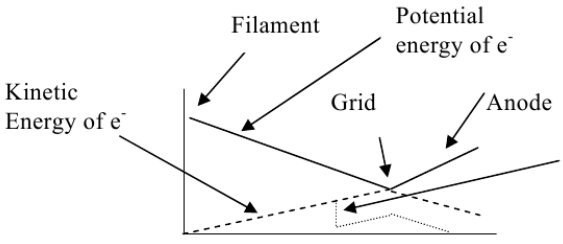


Figure 5: An electron which loses kinetic energy in a scattering event cannot make it all the way to the anode.

of the metal and become free. These free electrons are accelerated through the tube by the application of a voltage between the filament and the grid. The energy lost by the electrons can be measured by looking at the current through the vacuum tube as a function of voltage.

A schematic of the setup is shown in Fig. 3 and the electrical circuit is shown in Fig. 4. A potential energy and kinetic energy diagram of the electrons is show in Fig. 5. Electrons are accelerated from the filament (blue) to the grid (red) by a positive voltage. There is then a slightly negative voltage applied between the grid and the anode (black) which repels the electrons. If the electrons do not lose any energy going from the filament to the grid, then they have enough kinetic energy to continue on, and be collected in the anode [8]. However, if the electrons lose energy on the way to the anode, they may not have enough energy to overcome the slight potential barrier between the anode and the grid. They will then be collected by the grid, instead of by the anode. The anode current is thus a measure of how many electrons passed through the mercury without losing energy.

[8] In a vacuum tube electrons move from the cathode to the anode. In this case the filament would be the cathode. This is why electrons are sometimes called cathode rays, as in a cathode ray tube or CRT for a television set.

It is also possible for an electron to collide with more than one Hg atom on its way to the cathode. In this case it will lose twice as much energy as it would lose for a single collision. A typical plot of anode current vs. voltage is shown in Fig. 6. As the accelerating voltage increases more electrons flow to the anode and the current increases. However, when the kinetic energy of the electrons is enough to excite a transition from one internal state of the Hg atom to another, then electrons can lose kinetic energy in inelastic collisions, and the current decreases. The current begins to increase with further accelerating voltage until the electrons have enough energy to excite a second transition in another Hg atom, thus giving the second dip. This process then repeats as the voltage continues to increase.

Note that in the newer setups the voltage vs. current curve will be displayed on an oscilloscope. There is a digital camera you can use to photograph the scope to get a hard copy of this for your reports.

Prelab Questions

1. How can you determine the uncertainty in your value for the excitation potential?

2. As you measured in the earlier spectroscopy labs, mercury emits light when excited by an electric current. Explain the relationship between the light emitted by the mercury and the energy lost by electrons during a collision. Give a formula to compare the wavelength of the light and the voltage difference between successive

peaks in the Frank-Hertz curve.

3. Redraw Fig. 5 for the case where an electron loses energy in two collisions.

4. Redraw Fig. 5 for the case where an electron loses energy in one collision, but still has enough potential energy to be collected in the anode.

5. Predict the effect of increasing the filament current on the experiment.

6. Predict the effect of increasing the retarding voltage on the experiment.

7. Predict the effect of increasing oven temperature on the experiment.

Introduction

1. Describe the Frank-Hertz experiment and what will be measured.

2. Discuss the difference between measuring atomic states using light spectroscopy and using electron spectroscopy.

3. What is the difference between an *elastic* and *inelastic* collision?

Procedure

1. Draw a schematic of the experiment and label the parts.

2. Describe the steps required to get the best results. Which values of filament current, temperature, retarding potential etc. did you use.

3. Discuss how sensitive the experiment was to the various settings. Did some voltages have to be exactly adjusted, were others less sensitive?.

Data and Analysis

1. Calculate the excitation voltage with the appropriate uncertainty. Base the uncertainty on how accurately you can measure the position of the peaks.

2. Compare the excitation voltage to the measured wavelength of light emitted by mercury gas. Which transition are we observing?

Conclusions

1. Compare electron spectroscopy with optical spectroscopy as a means of measuring atomic excitations.
2. Describe how you might improve the experiment.

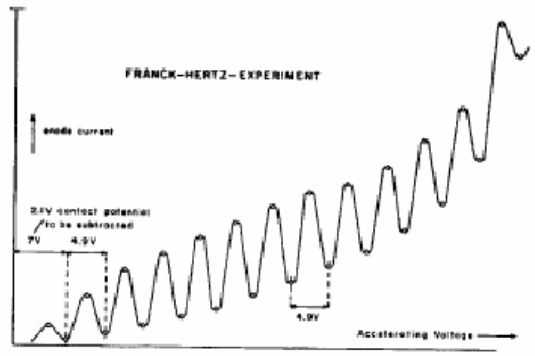


Figure 6: Output.

Radioactive decay

Concepts covered in this lab

- Radioactive decay.
- Geiger counters (see Appendix).
- Statistical uncertainties (counting statistics).

Introduction

This lab introduces the use of a Geiger counter, the principles of radioactive decay, counting statistics, half life, and attenuation. A short lived radio-nuclide is generated by separating the daughter nuclide $^{137}Ba^{*}$, from its longer lived parent nuclide ^{137}Cs. The decay of the $^{137}Ba^{*} \rightarrow ^{137}Ba + \gamma$, occurs with a half life of 2.55 min. In the first half of this lab the half life and statistical properties of the decay will be measured using a Geiger counter. In the second half of the lab the energy of beta particles will be measured by finding the thickness of aluminum required to stop the radiation and comparing this with the calculated stopping power of aluminum.

Geiger Counter Calibration

For the first part of the laboratory you will calibrate the optimum voltage setting for the Geiger counter. Use one of the sealed sources for this part. Start out with a voltage setting of 300V and measure the number of counts in a 10 s interval. Now increase the voltage setting in steps of 50 V and continue to make 10 s measurements. Plot the number of counts as a function of voltage on a graph. For small voltage settings the discharge in the Geiger tube will not always trigger a count, and you should see the number of counts decrease with decreasing voltage. For large voltage settings you will get spontaneous discharge of the counter, and see too many counts. You should see a nice broad range in the middle where the number of counts is in-

dependent of the voltage. This is where you want to run the Geiger tube.

Half-Life Experiment

For the second part of the experiment you should prepare a solution of the $^{137}Ba^{*}$. Please wear the supplied gloves when working with the radioactive materials. The procedure is as follows:

1. Elution agent[9] will be drawn into a plastic syringe from a supplied bottle.
2. The syringe has a special adaptor to fit onto the housing of the isotope generator. The syringe will be screwed onto this adaptor while a protective cap is in place on the other side of the generator to prevent the elutant from leaking out.
3. The elutant with the radioactive daughter product will be pressed from the syringe into aluminum holders. The holders should then be placed in the aluminum plates and mounted into the Geiger tube setups.

[9] Elution means to remove a chemical by rinsing it with a solvent.

Once the radioactive sample has been placed in the holder, turn on the GM tube controller box to the optimum voltage determine in part 1. This will put the tube in a regime where each radioactive particle that gets stopped in the gas of the tube will create an avalanche of ionization and lead to a count. Record the number of counts acquired over 10 seconds. Repeat 10 second measurement at 20 second intervals for $\frac{1}{2}$ hour. These measurements will allow you to plot the decay in radioactive counts as a function of time and consequently extract the radioactive lifetime. When the experiment has been completed, the ^{137}Ba solution must be emptied into the radioactive waste bottle.

The error analysis of radioactive decay measurements differs from the error analysis that you have done previously because the uncertainties in the value of the counts is given by the square root of the number of counts, $\Delta N = \sqrt{N}$. As the activity of the ^{137}Ba gets smaller with time, you will collect fewer counts in the 10 second intervals and the value for the number of counts will become less reliable. The excel spreadsheet “fitexp" that you can download from the class web page takes this effect into account. From the fit parameters, extract the half-life of the radioactive decay. Make sure you also get an uncertainty value for the half life.

Counting Statistics

For the third part of the laboratory, we will use the sealed beta sources which have a long enough half-life that they can be assumed

to have a constant activity. By adjusting the position of the beta source or by using attenuators adjust the count rate in the Geiger tube to be around 100 counts/s. Now take 20 ten-second measurements of the count rate. Find the average and standard deviation of these measurements, and verify that the standard deviation of the number of counts for a measurement is equal to the square root of the number of counts.

Attenuation

For the fourth part of the laboratory you will measure the attenuation of the beta- radiation using absorbers of varying thickness. Select aluminum attenuators from the attenuator set, and gradually increase the thickness of aluminum between the beta source and the Geiger tube. There are several different beta sources available. Make sure you note down which one you are measuring. Note down the count rate for each value of attenuation. Keep increasing the attenuation until you reach a thickness where 99% of the original count rate has been attenuated. You may have to measure the number of counts per second when there is no source present and subtract out this background from your measurement. You can use combinations of attenuators to make up intermediate thicknesses if you want to be especially precise. Make a plot of the attenuation of the count rate vs. aluminum thickness (in mg/cm^2) (mg stands for miligram). Since the energy of the beta particles has a continuous distribution, the thickness of attenuation required to stop all the beta particles is an indication of the maximum, rather than the average energy of the betas. An approximate relation between the maximum range, R, of the beta's and the maximum energy, E, is given by:

$$R = 0.542E - 0.133 \text{ for } 0.8 < E < 3.0 \quad (7)$$

$$R = 0.407E^{1.38} - 0.133 \text{ for } 0.15 < E < 0.8 \quad (8)$$

Here E must be given in MeV, and R in g/cm^2 of aluminum. Estimate the maximum energy of the beta particles using this relationship, and compare this with the energy of the beta decay found from the CRC handbook nuclear isotope table. Estimate how accurately you know the thickness for 99% attenuation and use this to calculate an uncertainty in your estimate of the range.

Prelab Questions

1. What will be the value of the slope of a plot of ln(cnts/s) as a function of time in terms of the half-life?

2. If the earth is approximately 4 billion years old, how is it possible that there are radioactive materials around which have half lives significantly shorter than this time.

3. Why is it necessary to first remove the ^{137}Ba, from its longer lived parent nuclide ^{137}Cs before measuring the half life.

4. Explain why the thickness of the attenuators is measured in units of mg/cm^2. (mg stands for miligram)

Lab report guidelines

1. Introduction

   (a) Summarize the basic goals of the lab.

   (b) Describe how the short lived radioactive material will be produced.

2. Procedure

   (a) Draw a picture of the lab setup.

   (b) Describe how you calibrate the Geiger tube voltage. Include specifics of how you use the computer software to do this.

   (c) Describe how you made the half life measurement.

   (d) Describe how you did the attenuation measurement.

3. Data and analysis

   (a) Plot a graph of the Geiger counter counts vs voltage. You can download the data from the computer into an excel spreadsheet format.

   (b) Plot a graph of ln(cnts) vs. time for you half-life measurements. Fit this to a straight line and plot the fit on top of the data.

   (c) Make sure to properly label and document all your graphs.

   (d) Calculate half-life and its uncertainty from your data.

   (e) Plot the counts vs. attenuator thickness for you range-energy data.

   (f) Estimate the maximum beta particle energy, and your uncertainty in this value.

4. Conclusions

   (a) Compare you half-life value to the expected value and comment on how well you were able to measure this quantity.

(b) Compare you estimated beta-particle energy with the expected energy of the beta. To find the expected energy, you need to look up the decay of the particular beta- source you used in the CRC nuclear data table.

(c) Suggest ways in which the experiment might be improved.

Appendices

Appendix: How to work with Experimental Uncertainties

> I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely in your thoughts advanced to the state of Science, whatever the matter may be
>
> Lord Kelvin (Sir William Thompson)

Experimental Errors

Since any physical measurement is imperfect, one must report the value of a quantity together with the uncertainty or error in the reported value. For example, one might measure the diameter of a US penny to be 19.1 ± 0.3 mm. This gives the value (19.1), the units, (mm) and the error in the value $\pm$ 0.3. This section will discuss error analysis, which comprises the methods used to handle experimental error.

The determination of the value for the experimental error can be a subtle issue. The person doing the measurement needs to think carefully about how the quantity is being measured and what aspect of that measurement might lead to error. For example, if I measure the diameter of a penny, one can imagine a number of possible sources of experimental error: (1) the accuracy of the manufacture of the ruler, (2) the thermal expansion of the ruler, (3) the alignment of the ruler with the center of the penny, (3) the degree to which one can estimate distances between the markings on the ruler and (4) the variation between different pennies. The experimenter needs to decide which of these factors are important. For the case of the penny, (3) probably dominates all the others.

Types of Experimental Error

There are two main types of experimental error; random and systematic. Random error is due to things like noise in a voltmeter or variations in the number of radioactive decays from an isotope. Systematic errors are due to aspects of your experimental setup which are biased in one way or another, but which would not change if you repeated the measurement many times. Random errors are much easier to deal with than systematic errors. When you have a random error, the size of that error decreases if you make many measurements and average them together. In addition, by repeating a measurement over and over and seeing how much it changes, you can estimate the size of a random error. Systematic errors are more difficult. You have to estimate the size of a systematic error by thinking very carefully about the measurement.

Accuracy and Precision

When making a measurement with an instrument one usually obtains a result with a certain number of significant digits. For example, a voltmeter might return a value of 3.2275 V. The number of digits tells you the precision of the measurement. However, it is certainly possible that the experimental error is larger than the precision. For example the error may be $\pm 0.2V$. In this case the accuracy of the voltage reading is ± 0.2 even though the precision is 3.2275.

Mistakes are not Experimental Error

Do not confuse a mistake (or human error) with experimental error. For example, if you multiply 6x7 and get 43, this is not experimental error, it is just a mistake. It should not be reported in a lab writeup, it should be found and fixed. If you are counting fringes in a Michaelson interferometer and you loose track of how many you counted that is a mistake not experimental error. You need to restart the experiment and do it again. Note that sometimes you can find and fix mistakes. If your data for the number of fringes are 257, 258,257,256,150,257,258, then you can throw out the value of 150, since it is almost certainly a mistake rather than experimental error.

Comparing Your Data to Accepted Values

Typically, when you do an experiment you will compare the results which you find to the commonly accepted, or tabulated value. For example you will do a lab to measure the ratio of the electron charge to its mass. The accepted value of this ratio is $1.758820088(39) \times 10^{11}$

C/kg. In your lab you might measure $1.93 \pm 0.08 \times 10^{11}$. The experimental error is the 0.08, not the difference between this value and the tabulated value. In your lab report conclusion you should, however, comment on whether the difference between the tabulated value and your measurement falls within your experimental error.

Averages and Standard Deviations

The easiest type of experimental error to work with is random error, so we will assume that the error is of that type. For the case of random error, if you measure a quantity many times the random errors will partially cancel out. This is because sometimes the error will be in the + direction and sometimes in the - direction. The average of all your measurements is therefore a more accurate estimate of the quantity you are measuring. Suppose you make N measurements of a quantity x. These individual measurements can be labeled $x_1, x_2, ...x_i, ...x_N$. Then your best estimate of the true value of x, is the mean, or average $\langle x \rangle$ defined by:

$$\langle x \rangle = \frac{1}{N} \sum_{i=1}^{N} x_i.$$

The simplest way to determine the magnitude of a random error is look at how much each of the measurements deviates from the mean. This is typically measured by a quantity σ called the standard devaition which is defined by:

$$\sigma = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (x_i - \langle x \rangle)^2} \tag{9}$$

In eq. 11 σ is the deviation of a single measurement. The deviation of the mean itself, σ_{mean} is smaller by the square root of the number of measurements, e.g. :

$$\sigma_{mean} = \sigma/\sqrt{N} = \sqrt{\frac{1}{N(N-1)} \sum_{i=1}^{N} (x_i - \langle x \rangle)^2} \tag{10}$$

Error Propagation

Often, the quantity you measure is not the final result you are interested in. Here are rules for propagating errors through calculations.

- If $C = A + B$ then $\Delta C = \sqrt{\Delta A^2 + \Delta B^2}$.
- If $D = A + B + C$ then $\Delta D = \sqrt{\Delta A^2 + \Delta B^2 + \Delta C^2}$.
- If $C = A - B$ then $\Delta C = \sqrt{\Delta A^2 + \Delta B^2}$.

- If $C = A \times B$ then $\frac{\Delta C}{C} = \sqrt{\left(\frac{\Delta A}{A}\right)^2 + \left(\frac{\Delta B}{B}\right)^2}$.
- If $C = A/B$ then $\frac{\Delta C}{C} = \sqrt{\left(\frac{\Delta A}{A}\right)^2 + \left(\frac{\Delta B}{B}\right)^2}$.
- If $C = A^n B^m$ then $\frac{\Delta C}{C} = \sqrt{\left(\frac{n\Delta A}{A}\right)^2 + \left(\frac{m\Delta B}{B}\right)^2}$.
- If $C = f(A)$ then $\Delta C = \left|\frac{df}{dA}\Delta A\right|$.

Linear Fits

Sometimes rather than having a series of measurements for the same quantity, you will obtain the variation of a quantity, y_i as a function of a parameter x_i. You also have, somehow, estimated the error in each measurement with the value Δy_i. For example, you might be measuring velocity as a function of time under conditions of constant acceleration. In this case you expect the data to lie along a line given by $y = mx + b$. Here m is the slope and b the y-intercept. We will provide python software which can determine the values of m and b for the best fit line to the data along with their uncertainties Δm and Δb.

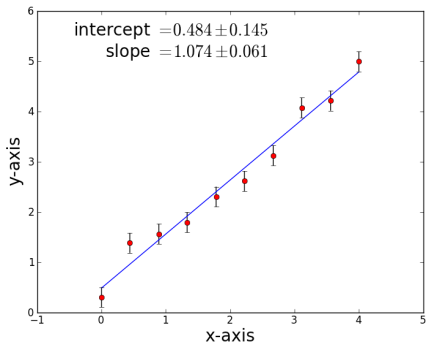


Figure 7: Linear fit to X-Y data

What the software does is calculates the mean square devation of all the points from the fitted line:

$$F(m,b) = \sum_{i=1}^{N} (y_i - m * x_i + b)^2 . \tag{11}$$

It then minizes $F(m,b)$ by solving for $\frac{dF}{dm} = 0$ and $\frac{dF}{db} = 0$. The uncertainties Δm and Δb are obtained by finding the error in this calculation based on the propagation of error rules discussed above.

Appendix: Wave nature of light

Interference in waves

For many experiments, light can be considered a wave. We remind ourselves that a phase difference can be brought about because of a difference in path lengths between two sources.

This leads to the prediction that light coming from coherent sources, one can observe both *constructive interference* and *destructive interference*, as we see in Fig. 8.

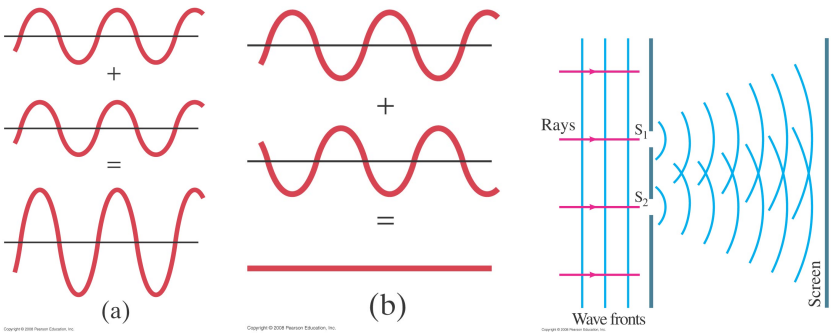


Figure 8: Addition of waves leading to constructive and destructive interference (Fig. 34-8 (a,b)) and two slits which act as two coherent sources (Fig. 34-6). **?**

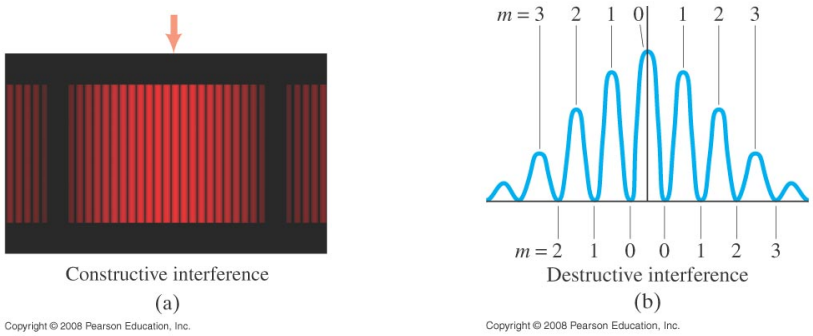


Figure 9: Photograph and diagram of interference pattern resulting from two-slit experiment. Fig. 34-9. **?**

This interference effect can be seen clearly in a double-slit experiment and the equations for the location of the maxima (bright) and minima (dark) are given below, assuming a distance d between the two slits. You can see a picture and diagram of this in Fig. 9.

$$d\sin(\theta) = m\lambda \qquad (m = 0, 1, 2, ...) \qquad \textbf{constructive interference}$$

$$d\sin(\theta) = (m + \frac{1}{2})\lambda \qquad (m = 0, 1, 2, ...) \qquad \textbf{destructive interference (dark).}$$

Appendix: Diffraction gratings and spectrometers

Diffraction gratings

A large number of parallel slits is called a *diffraction grating*, although it would be better to refer to it as an interference grating.

Generally produced by cutting fine lines in a glass plate. Can be up to 10,000 lines per cm!

We still make use of the same equation as we used in the double-slit experiment.

$$\sin\theta = \frac{m\lambda}{d} \qquad m = 0, 1, 2, 3, \ldots \qquad \text{[principle maxima]}$$

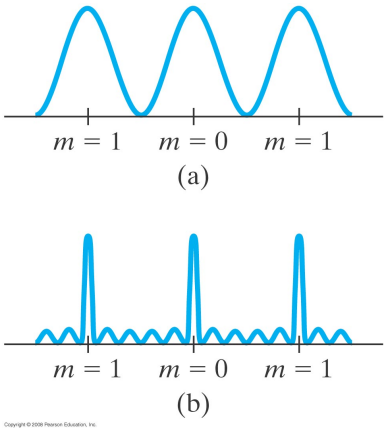


Figure 10: Intensity as a function of viewing angle for (a) two slits and (b) six slits. Fig. 35-18

As we see in Fig. 10, because of the geometry of the diffraction grating, and the fact that the distance between the slits (d) is so much smaller, we get more sharply defined and wider spaced peaks.

Warning! Note that often the diffraction grating is described in # of gratings per distance! So it is up to you to convert this to d for the equations!

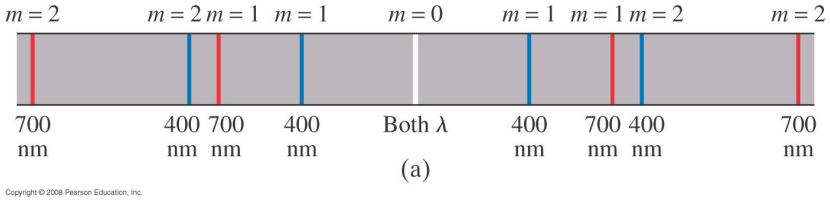


Figure 11: Spectra produced by a grating for (a) two wavelengths. Fig. 35-19 **?**

Spectrometer

A spectrometer is a device used to measure wavelengths accurately using a prism or a diffraction grating, as shown in Fig. 12. By splitting up the wavelengths and finding out where the maxima land on the viewing surface, one can make very good determinations of the wavelength(s) of the incoming light.

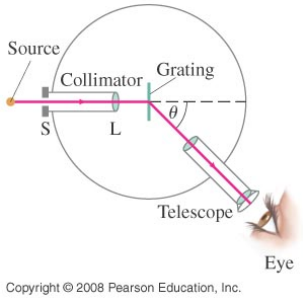


Figure 12: Spectrometer. Fig. 35-21

Appendix: Interferometers

Michelson interferometer

Albert Michelson (1852-1931). Developed the interferometer. (see figure 13) He developed this to see if the speed of light was affected by the direction of the Earth's rotation through some medium, called *the aether*.

Turns out to be **very, very, very** sensitive to small changes in the movement of one of the mirrors. (walk through interferometer diagram)

Discussion question: How far (in terms of λ) does the mirror M_1 have to be moved to get destructive interference where there had been constructive interference?

A: $\frac{\lambda}{4}$. For blue light at 400 nm this corresponds to a shift in 100 nm! How much of a mm is this? ($\frac{1}{10000}$ of mm)

One can see that this might be useful in measuring small changes in length like a strain on some material that bends/compresses/expands the material in only one direction.

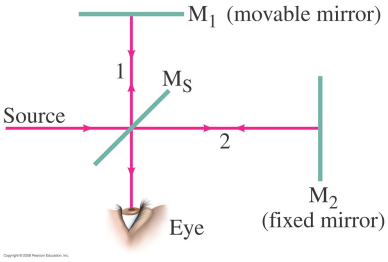


Figure 13: Michelson interferometer. Fig.34-24

Appendix: Atomic spectra

Atomic spectra

Planck's quantum hypothesis

Max Planck (1858-1947), was theoretical physicist in Germany who had spent much of his career thinking about thermodynamics. He knew some of the experimentalists who were measuring the black-body spectrum and felt he needed to come up with a consistent explanation. He pictured the objects that emitted the EM radiation as small oscillating objects that generated radiation according to Maxwell's equations. With this picture, he came up with *an empirical formula that fit the data perfectly!* This formula became known as Planck's radiation formula.

$$I(\lambda, T) = \frac{2\pi hc^2\lambda^{-5}}{e^{hc/\lambda kT} - 1}$$

Where h was a constant that he figured out by fitting the experimental data.

$$h = 6.626 \times 10^{-34} J \cdot s$$

In deriving this formula, he assumed that the energy put out by these oscillating objects is proportional to the energy.

$$E = hf$$

But to get his equation to work out, he needed to assume that the energy could only come in discrete amounts. The energy is restricted to multiples of a certain number and the energy is emitted in *discrete packets.*

$$E = nhf \qquad n = 1, 2, 3, ...$$

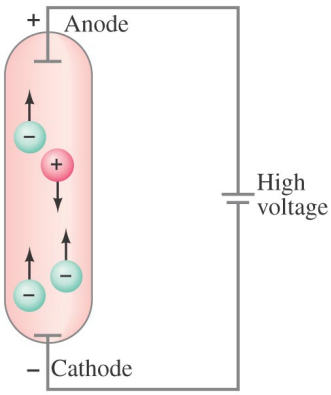
This is often called **Planck's quantum hypothesis.** But even though it gave him the right answers, Planck did not know how to interpret this result! In fact, he continued to try to come up with an alternative explanation for this result that preserved the continuous nature of energy.

Photon theory of light and the photoelectric effect

In 1905, about 5 years after Planck's quantum hypothesis, Einstein postulated that light is *always* emitted or absorbed in *packets* of energy, where the amount of energy in each packet is hf; i.e., light of higher frequency comes in larger packets of energy that light of lower frequency.

Einstein's energy packets are now called "photons"; i.e., a photon is packet (or *quanta*) of electromagnetic energy. The energy carried by a single photon is proportional to its freqency: $E = hf$. Photons in blue light each carry more energy than photons in red light, because the frequency of blue light is greater than that of red light.

Atomic spectra



(a)

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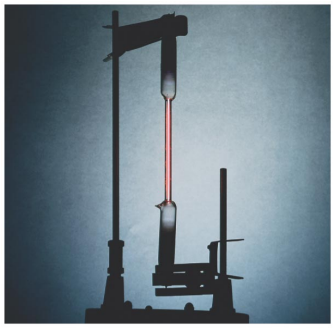

(b)

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Figure 14: Gas-discharge tube: (a) diagram; (b) photo of an actual discharge tube for hydrogen. Fig.37-19. **?**

(a)

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Figure 15: Emission spectra of the gas (a) atomic hydrogen. Fig.37-20. **?**

It is known (and was known in the early 1900s) that when a pure gas is heated, it gives off light. This is generally done using a *discharge tube* (see Fig. 14). When this light is put through a spectrometer (diffraction grating) it was found that the light is not coming out in all colours (pure rainbow pattern in spectrometer), but instead is emitted in *discrete* colours! (see Fig. 15) This **emission spectrum** serves as a "fingerprint for the gas, as it will be different for each gas. It can also be seen that gases will *absorb* light of these specfic colours and so can produce an *absorption spectrum* which is an inverse of their emission spectrum.

Hydrogen is the simplest atom with only the one electron and has the simplest spectrum (see Fig. 15 and Fig. 16).

It has a very regular pattern which invited scientists to try to figure out an equation to explain this pattern.

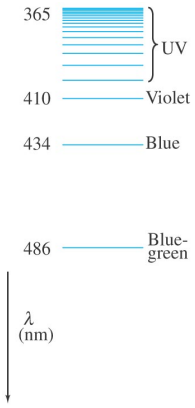

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Figure 16: Balmer series of lines for hydrogen. Fig.37-21. **?**

Appendix: Franck-Hertz experiment

"It might interest you to know that when we made the experiments that we did not know Bohr's theory. We had neither read nor heard about it. We had not read it because we were negligent to read the literature well enough – and you know how that happens. On the other hand, one would think that other people would have told us about it. For instance, we had a colloquium at that time in Berlin at which all the important papers were discussed. Nobody discussed Bohr's theory. Why not? The reasons is that fifty years ago, one was so convinced that nobody would, with the state of knowledge we had at that time, understand spectral line emission, so that if somebody published a paper about it, one assumed, "Probably it is not right." So we did not know it. But we made that experiment (and got the result that confirmed Bohr's theory) because we hoped that if we found out where the borderline between elastic and inelastic impact lies ... only one line might appear. But we did not know whether that would be so, and we did not know whether at all an emission of an atom is of such a type that one line alone can be emitted and all the energy can be used for that purpose. The experiment gave it to us, and we were surprised about it. But we were not surprised after we read Bohr's paper later, after our publication."

– Excerpt from one of three recordings of J. Franck, made in connection with a film on the Franck-Hertz experiment at Educational Services, Inc., Watertown, Massachusetts, in January, 1961. As transcribed in "On the recent past of physics", by Gerald Holton, American Journal of Physics, vol. 29, p. 805 (1961). [10]

[10] http://spiff.rit.edu/classes/phys314/lectures/fh/fh.html

Appendix: Geiger counters

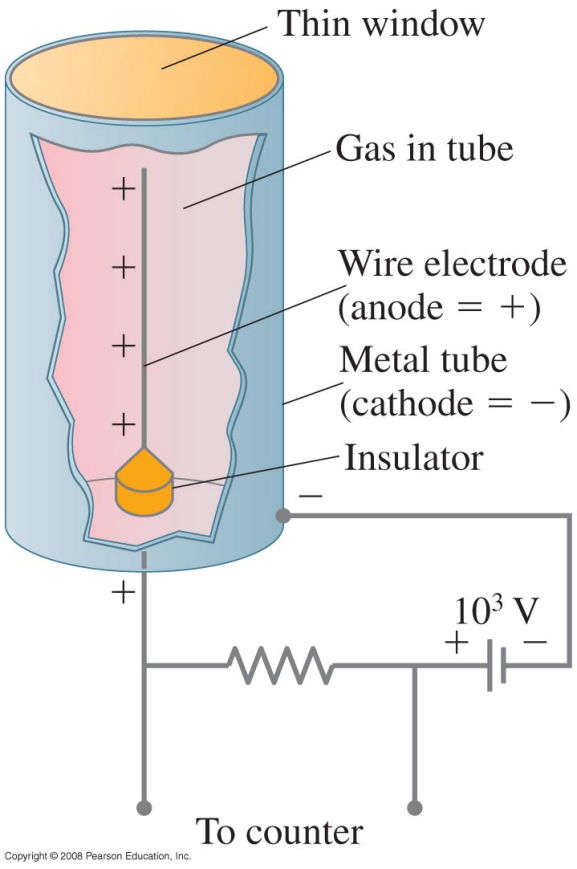


Figure 17: Diagram of a Geiger counter.
?

Appendix: Equipment manuals

Electron charge/mass ratio equipment

Determination of the Specific Charge of the Electron

Objects of the Experiment

- Study of the deflection of electrons in a magnetic field into a circular orbit.
- Determination of the magnetic field B as a function of the acceleration potential U of the electrons at a constant radius r.
- Determination of the specific charge of the electron.

Principles

The mass m_e of the electron is hard to come by experimentally. It is easier to determine the specific charge of the electron

$$\varepsilon = \frac{e}{m_e} \qquad \text{(I)},$$

from which the mass m_e can be calculated if the elementary charge e is known:

An electron moving at velocity v perpendicularly to a homogenous magnetic field B, is subject to the Lorentz force

$$F = e \cdot v \cdot B \qquad \text{(II)}$$

which is perpendicular to the velocity and to the magnetic field. As a centripetal force

$$F = m_e \cdot \frac{v^2}{r} \qquad \text{(III)}$$

it forces the electron into an orbit of radius r (see Fig. 1), thus

$$\frac{e}{m_e} = \frac{v}{r \cdot B} \qquad \text{(IV)}.$$

In the experiment, the electrons are accelerated in a fine beam tube by the potential U. The resulting kinetic energy is

$$e \cdot U = \frac{m_e}{2} \cdot v^2 \qquad \text{(V)}.$$

The specific charge of the electron thus is

$$\frac{e}{m_e} = \frac{2 \cdot U}{(r \cdot B)^2} \qquad \text{(VI)}.$$

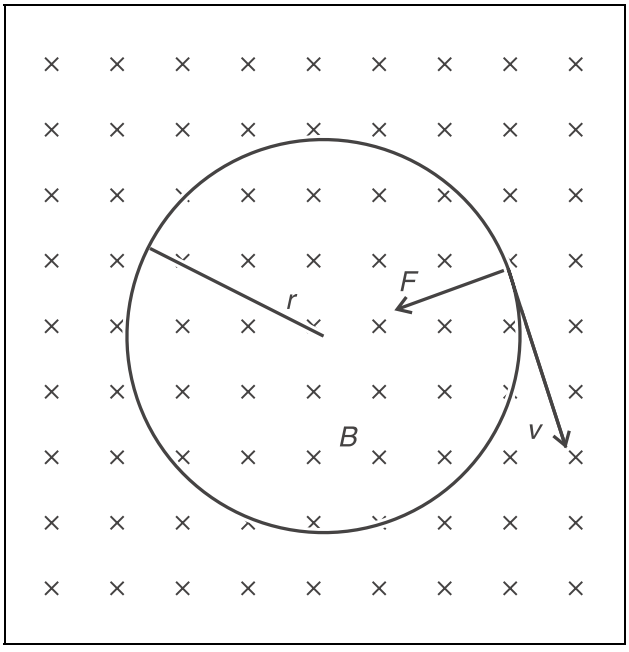


Fig. 1 Deflection of electrons in a magnetic field B by the Lorentz-force F into a circular orbit of a given radius r.

Apparatus

1 Fine beam tube	555 571
1 Helmholtz coils with holder and measuring device	555 581
1 DC power supply 0 ... 500 V	521 65
1 DC power supply 0 ... 20 V	521 54
1 Voltmeter, DC, $U \leq 300$ V e.g.	531 100
1 Ammeter, DC, $I \leq 3$ A e.g.	531 100
1 Steel tape measure, 2 m	311 77
3 Safety connecting leads, 25 cm	500 614
3 Safety connecting leads, 50 cm	500 624
7 Safety connecting leads, 100 cm	500 644
additionally recommended:	
1 Teslameter	516 62
1 Axial B-probe	516 61
1 Multicore cable, 6-pole, 1,5 m long	501 16

Safety notes

Attention: The fine beam tube requires dangerous contact voltages up to 300 V for accelerating the electrons. Other voltages that are connected with this dangerous contact voltage also present a contact hazard. Dangerous contact voltages are thus present at the connection panel of the holder and at the Helmholtz coils when the fine beam tube is in operation.

- Connect the connection panel only via safety connecting leads.
- Always be sure to switch off all power supplies before connecting and altering the experiment setup.
- Do not switch on the power supplies until you have finished assembling the circuit.
- Do not touch the experiment setup, particularly the Helmholtz coils, during operation.

Danger of implosions: The fine beam tube is a evacuated glass vessel with thin walls.

- Do not subject the fine beam tube to mechanical stresses.
- Operate the fine beam tube only in the holder (555 581).
- Connect the 6-pole plug of the holder carefully to the glass base.
- Read the instruction sheet supplied with the fine beam tube.

The fine beam tube contains hydrogen molecules at low pressure, which through collisions with electrons are caused to emit light. This makes the orbit of the electrons indirectly visible, and their orbiting radius r can be directly measured with a ruler.

The magnetic field B is generated in a pair of Helmholtz coils and is proportional to the current I in the Helmholtz coils:

$$B = k \cdot I \qquad \text{(VII)}.$$

The dependence on the accelerating potential U of the current I, in the magnetic field of which the orbiting radius of the electrons is kept to a constant value r, follows after recasting equations (VI) and (VII)

$$U = \frac{e}{m_e} \cdot \frac{1}{2} \cdot r^2 \cdot k^2 \cdot I^2 \qquad \text{(VIII)}.$$

The proportionality factor

$$k = \mu_0 \cdot \left(\frac{4}{5}\right)^{\frac{3}{2}} \cdot \frac{n}{R} \qquad \text{(IX)}$$

$\mu_0 = 4\pi \cdot 10^{-7} \frac{\text{Vs}}{\text{Am}}$: magnetic field constant

can be calculated either from the coil radius R = 150 mm and the winding factor n = 130 per coil, or be determined by recording a calibration curve $B = f(I)$. All determining factors for the specific electron charge are now known.

Setup

Note:

Perform measurements in a dark chamber.

Helmholtz coils may be charged with more than 2 A for short time only.

The experimental setup to determine the specific electron charge is shown in Fig. 2, the electric connections in Fig. 3.

– Disconnect power supply and turn all rotary potentiometers to left catch position.
– Connect the 6.3-V input end of the fine beam tube to the 6.3-V outlet of the DC power supply.
– Short-circuit the positive pole of the 50-V outlet of the DC power supply with the negative pole of the 500-V outlet and connect with the socket "-" of the fine beam tube (cathode).
– Connect the socket "+" of the fine beam tube (anode) with the positive pole of the 500-V outlet, the socket W (Wehnelt-cylinder) with the negative pole of the 50-V outlet.
– In order to measure the acceleration potential U connect the voltmeter (measuring range 300 V–) to the 500-V outlet.
– Short the deflection plates of the fine beam tube to the anode.
– Connect the DC power supply and ammeter (measuring range 3 A–) in series with the Helmholtz coils.

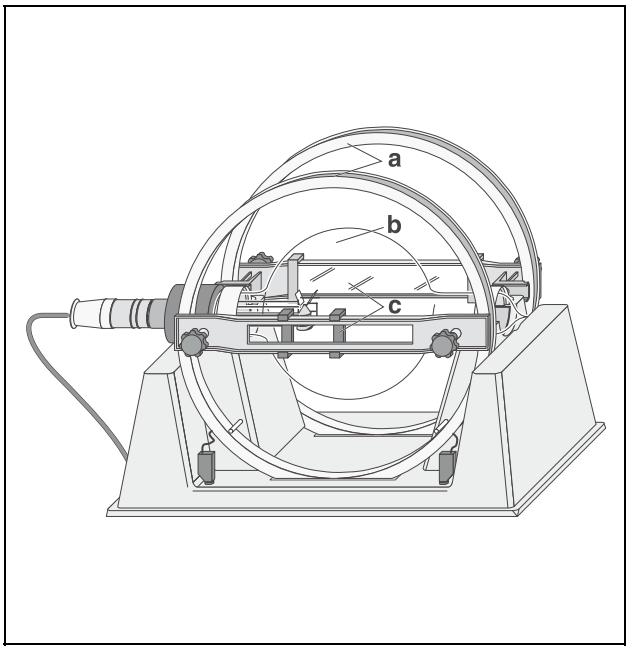


Fig. 2 Experiment setup for determining the specific electron charge
a Helmholtz coils
b Fine beam tubes
c Measuring device

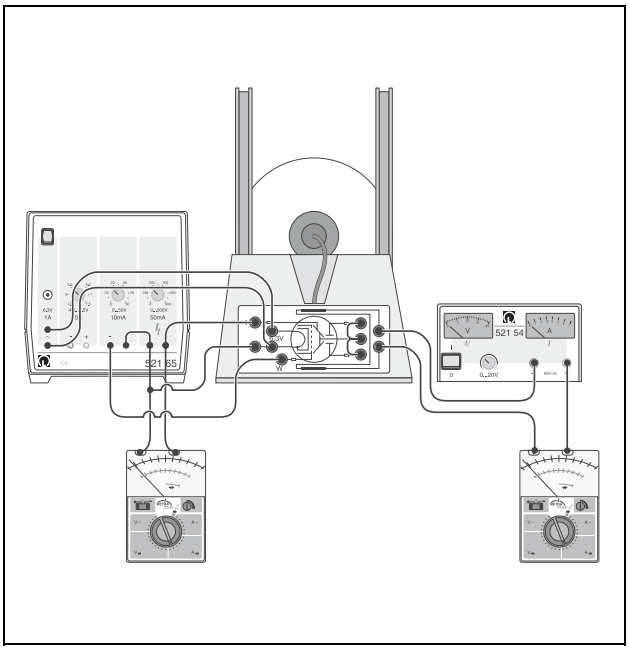


Fig. 3 Electric connection

– Power up the DC power supply and set acceleration potential *U* = 300 V.

  Thermionic emission starts after warming up for a few minutes.

– Optimize focussing of the electron beam by varying the voltage at the Wehnelt-cylinder from 0 … 10 V until it leads to a narrow, well defined beam with clear edge definition.
– Connect the DC power supply of the Helmholtz coils and look for current *I*, at which the electron beam is deflected into a closed orbit.

If the electron beam after leaving the anode is deflected to the wrong (left) side:

– disconnect both power supplies.
– exchange the connections at the DC power supply in order to change the polarization of the magnetic field.

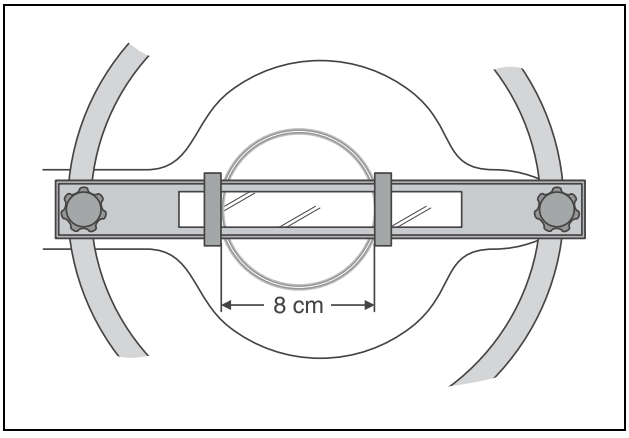
If the electrons do not move on a closed orbit but on a helical curve line:

– Loosen the mounting bolts of both holding brackets (read the information manual for the fine beam tube).
– Carefully rotate the fine beam tube around its longitudinal axis, until the electron beam runs on a closed circular orbit.
– Fasten mounting bolts.

Carrying out the experiment

– Move the left slide of the measuring device so that its inner edge, mirror image and escape aperture of the electron beam come to lay on one line of sight.
– Set the right slide for both inside edges to have a distance of 8 cm.
– Sight the inside edge of the right slide, align it with its mirror image and adjust the coil current *I* until the electron beam runs tangentially along the slide edge covering the mirror image (see Fig. 4).
– Reduce the acceleration potential *U* in steps of 10 V to 200 V and choose the coil current *I* so that the orbit of the electron beam has a diameter of 8 cm.
– Record acceleration potential *U* and coil current *I*.

Fig. 4 Measurement of the orbit diameter with the measuring device



Calibration of the Helmholtz magnetic field (optional):

The setup for calibrating the magnetic field is shown in Fig. 5. The additionally recommended devices mentioned above are required for making measurements.

– If applicable disconnect all power supply units.
– Remove the measuring device and the Helmholtz coil at the front side, loosen the connection to the fine beam tube and the mounting bolts of the two holding brackets (read the instructions for the fine beam tube).
– Carefully remove the fine beam tube and place it e. g. in its original case.
– Re-assemble the Helmholtz at the front side coil and connect.
– Connect the axial B-probe to the Teslameter (measuring range 20 mT) and calibrate the zero-point (see Instruction Manual for Teslameter).
– Move the axial B-probe parallel to the magnetic field of the Helmholtz coils into the center of the pair of coils.
– Raise the coil current *I* from 0 to 3 A in steps of 0.5 A, measure the magnetic field *B,* and record the measured values.

After conclusion of the calibration:

– Re-assemble the fine beam tube according to the instructions.

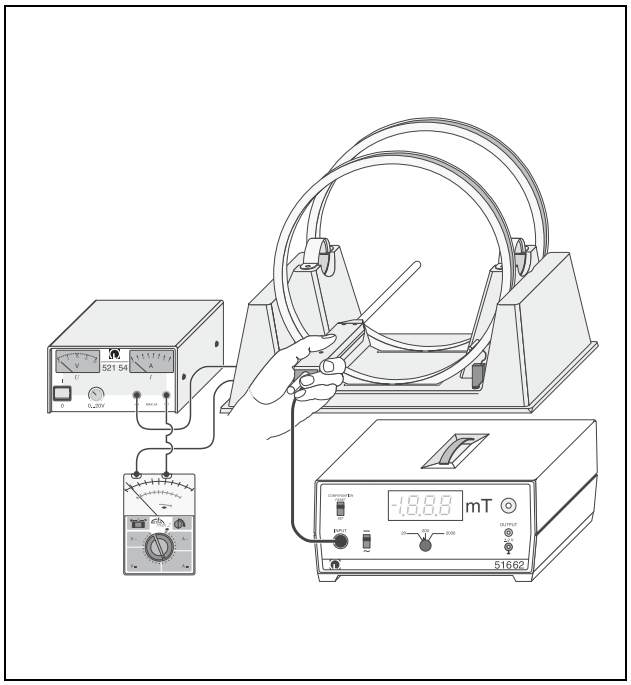


Fig. 5 Set-up for calibration of the Helmholtz magnetic field

Measuring example

Tab. 1: The Coil current *I* as a function of the acceleration potential *U* at constant orbit radius *r* = 0.04 m

$\frac{U}{\mathrm{V}}$	$\frac{I}{\mathrm{A}}$
300	2.15
290	2.10
280	2.07
270	2.03
260	2.00
250	1.97
240	1.91
230	1.88
220	1.83
210	1.79
200	1.75

Tab. 2: The Magnetic field *B* of the Helmholtz coils as a function of the coil current *I* (this measurement requires the above mentioned additionally recommended devices)

$\frac{I}{\mathrm{A}}$	$\frac{B}{\mathrm{mT}}$
0.5	0.35
1.0	0.65
1.5	0.98
2.0	1.34
2.5	1.62
3.0	2.05

Evaluation and results

In Fig. 6 the measured values from Tab. 1 are shown in their linear form $U = f(I^2)$ – according to (VIII). The slope of the resulting line through the origin is

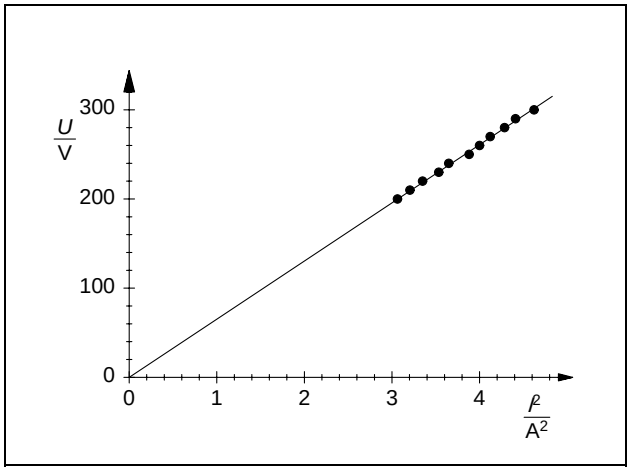
$\alpha = 65.3\ \mathrm{V\,A^{-2}}$.

According to equation (VIII), the specific electron charge is

$$\frac{e}{m_e} = \frac{2 \cdot \alpha}{r^2 \cdot k^2}$$

Further evaluation thus requires the proportionality factor *k*.

Fig. 6 Presentation of the measuring results from Tab. 1



Determination of the proportionality factor *k* from the calibration of the Helmholtz magnetic field:

Fitting of a straight line through the origin to the measuring values of Tab. 2 , or of Fig. 7 leads to

$k = 0.67\ \text{mT A}^{-1}$

and further

$$\frac{e}{m_e} = 1.8 \cdot 10^{11}\ \frac{\text{As}}{\text{kg}}$$

Calculation of the proportionality factor k:

Using (IX) one calculates

$k = 0.78\ \text{mT A}^{-1}$

and further

$$\frac{e}{m_e} = 1.3 \cdot 10^{11}\ \frac{\text{As}}{\text{kg}}$$

Documented value:

$$\frac{e}{m_e} = 1.76 \cdot 10^{11}\ \frac{\text{As}}{\text{kg}}$$

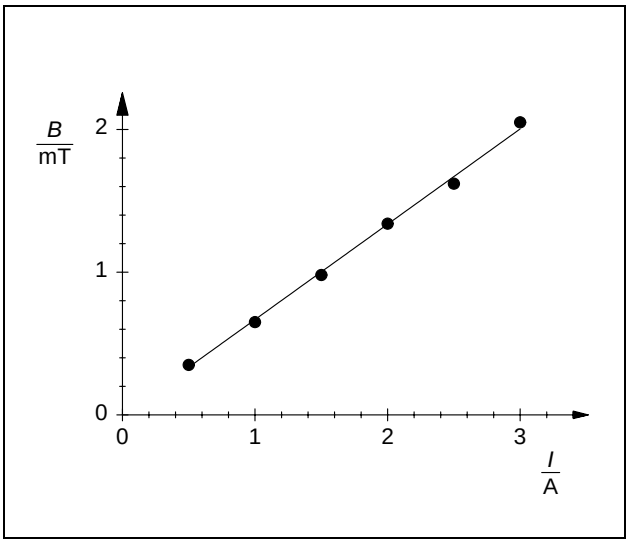


Fig. 7 Calibration curve for the magnetic field of the Helmholtz coils

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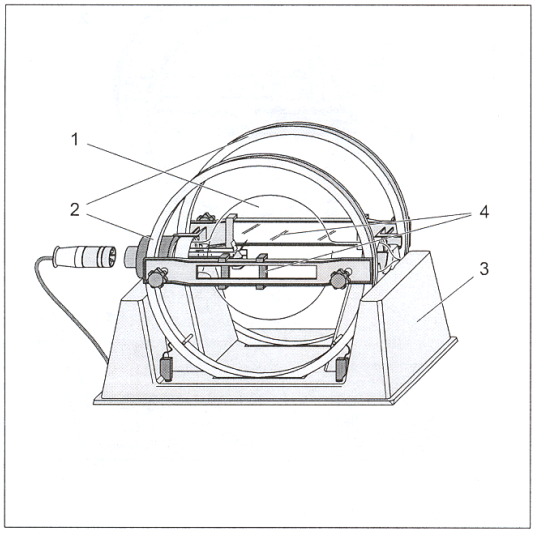


Instruction Sheet 555 571

Fine beam tube (555 571)
Helmholtz coils with holder and measuring device (555 581)

1 Fine beam tube
2 Helmholtz coils
3 Holder
4 Measuring device

The fine beam tube (555 571) is used in conjunction with the Helmholtz coils with holder and measuring device (555 581) to investigate the deflection of electron beams in electrical and magnetic fields, particularly the determination of the specific electron charge e/m.

The electron-beam system of the fine beam tube consists of an indirectly heated cathode, a conical anode from which the electrons emerge straight up, and a Wehnelt cylinder for focusing the electron beam. A pair of plates is positioned directly behind the anode for electrostatic deflection of the electron beam.

The Helmholtz coils with holder and measuring device (555 581) allow you to put the fine beam tube into operation and enable generation of a homogeneous magnetic field perpendicular to the electron beam of the fine beam tube. The operating voltages are connected in a clearly understandable fashion via safety sockets in the connection panel, which are internally connected with the sockets for the Helmholtz coils and connected to the electron beam system via a permanently attached cable. The measuring device, consisting of one straight member with two slides and one straight member with mirror, allows you to determine the diameter of a circular electron beam.

Safety notes

Attention: The fine beam tube requires dangerous contact voltages of up to 300 V for accelerating the electrons. Other voltages that are connected with this dangerous contact voltage also present a contact hazard. Dangerous contact voltages are thus present at the connection panel of the stand and at the Helmholtz coils when the fine beam tube is in operation.

- Connect the connection panel only via safety connecting leads.
- Always be sure to switch off all power supplies before connecting and altering the experiment setup.
- Do not switch on the power supplies until you have finished assembling the circuit.
- Do not touch the experiment setup, particularly the Helmholtz coils, during operation.

Danger of implosion: the fine beam tube is an evacuated glass vessel with thin walls.

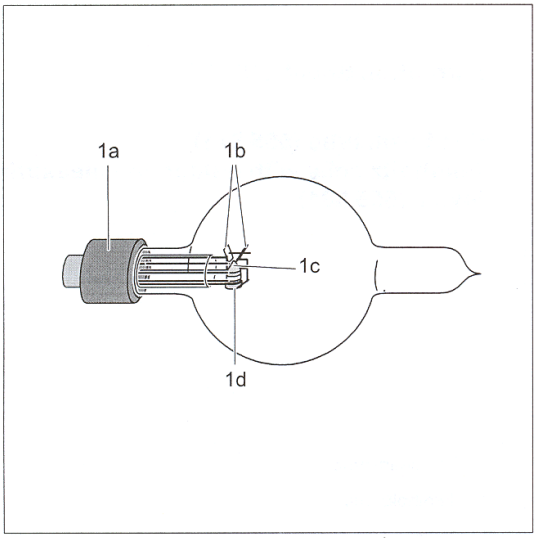
- Do not subject the fine beam tube to mechanical stresses.
- Use the fine beam tube only in the stand (555 581).
- Carefully connect the 6-pin plug of the stand to the base.

The fine beam tube can be destroyed by excessive voltages and currents, as well as by the wrong cathode temperatures.

- Do not exceed the operating parameters of the fine beam tube given in the technical data, particularly the maximum heating voltage of 6.3 V.

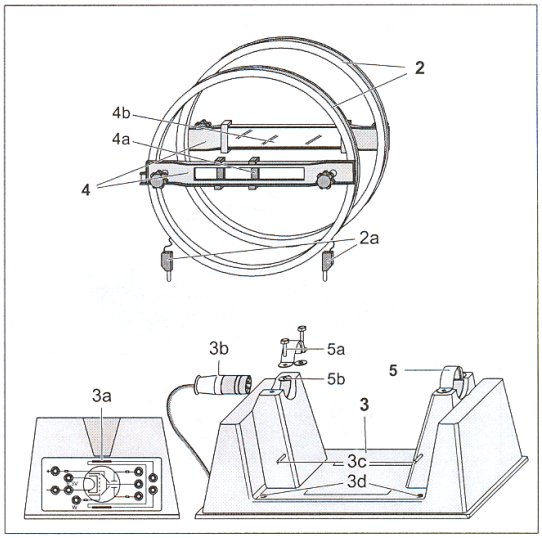
1 Scope of supply

1.1 Fine beam tube (557 571)



1 Fine beam tube
base (1a),
deflection plates (1b),
anode (1c),
cathode, Wehnelt cylinder (1d)

1.2 Helmholtz coils with holder and measuring device (555 581)



2 Pair of Helmholtz coils
4-mm plug (2a)

3 Holder
connection panel with diagram (3a), 6-pin plug (3b),
locking pins for Helmholtz coils (3c),
connection sockets for Helmholtz coils (3d)

4 Measuring device (catalog number: 555 59)
straight member with slides (4a), straight member with mirror (4b)

5 Retainer brackets
M4 screws (5a), washers (5b)

2 Technical data

2.1 Fine beam tube (557 571)

Glass bulb:

Gas filling:	hydrogen, approx. 1 Pa
Diameter:	16 cm

Glass base:

Connection:	6-pin

Electron beam system:

Heating voltage:	6.3 V
Heating current:	approx. 0.7-0.8 A
Anode voltage:	150-300 V DC
Wehnelt voltage:	±20 V
Plate voltage:	0-300 V DC

2.2 Helmholtz coils with holder and measuring device (555 581)

Pair of Helmholtz coils:

Number of turns:	130 per coil
Maximum coil current:	2 A (3 A transient)
Resistance:	approx. 2 Ω per coil
Coil radius:	150 mm
Coil spacing:	150 mm

Relationship between magnetic field B and coil current I:

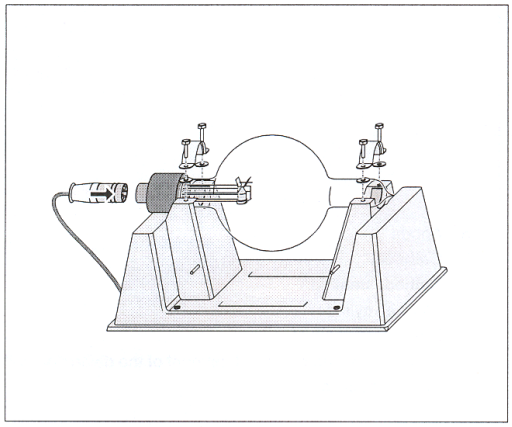
$$B = \mu_0 \cdot \left(\frac{4}{5}\right)^{\frac{3}{2}} \cdot \frac{n}{R} \cdot I$$

$\mu_0 = 4\pi \cdot 10^{-7} \frac{Vs}{Am}$: magnetic field constant

R: Coil radius
n: Number of turns = 130 per coil

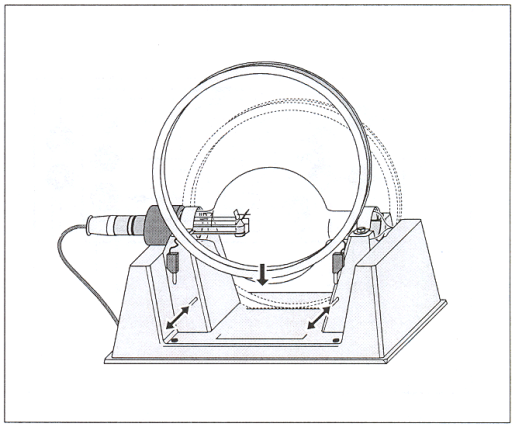
3 Assembly

3.1 Mounting the fine beam tube:



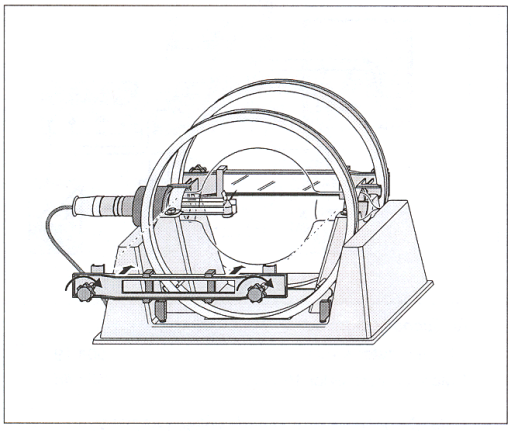
- Mount the fine beam tube so that the beam opening of the anode is pointing straight up.
- Alternately tighten the screws of the retainer brackets, being very careful to avoid one-sided mechanical stresses.
- Carefully connect the 6-pin plug to the glass base.

3.2 Mounting the Helmholtz coils:



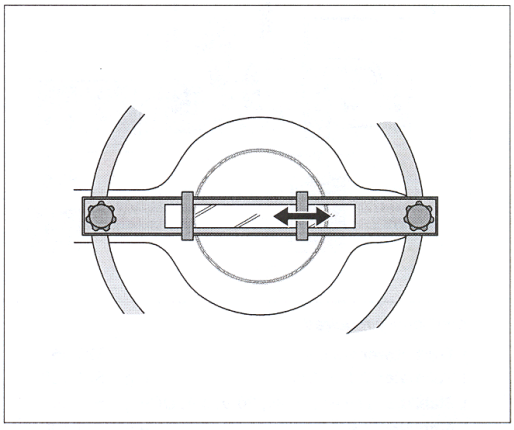
- Push the locking pins "forward", mount the "back" Helmholtz coil and plug the 4-mm connector into the corresponding socket.
- Push the locking pins "backward", and mount and connect the "front" Helmholtz coil.
- Set the pins in the middle position to hold both coils in place.

3.3 Attaching the measuring device



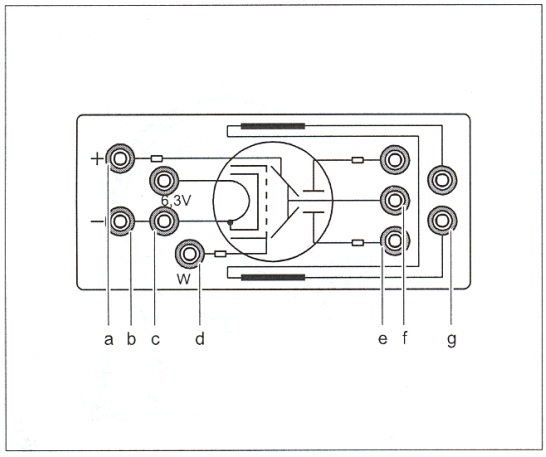
- Attach the straight member with mirror horizontally to the back Helmholtz coil and the member with two slides to the front Helmholtz coil.

3.4 Using the measuring device



- Move the left slide so that the inside edge, the mirror image and the beam aperture of the electron beam are in one line of sight.
- Move the right slide until the inside edge, mirror image and fine beam are in line.

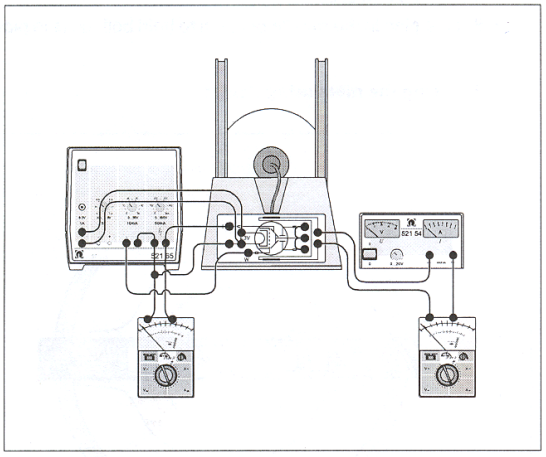
4 Socket assignments



a Anode
b Cathode
c Cathode heating
d Wehnelt cylinder
e Deflection plates
f Anode, for symmetrical adjustment of the deflection voltage
g Helmholtz coils

5 Operation

5.1 Determining e/m (deflection in a magnetic field)



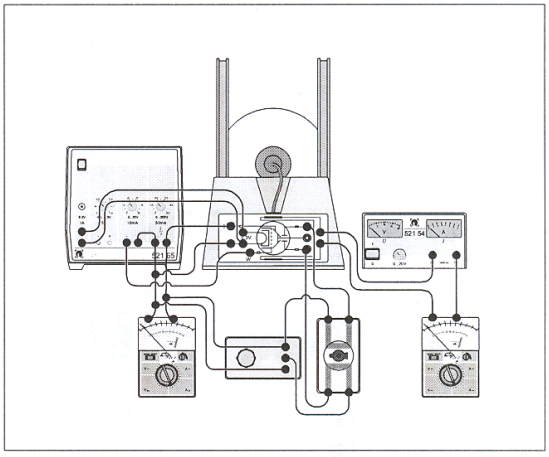
Additionally required:

1 Tube power supply		521 65
1 Voltmeter, 300 V DC	e.g.	531 100
1 Stabilized power supply, 20 V, 3 A, DC	e.g.	521 54
1 Ammeter, 3 A DC	e.g.	531 100

- Apply the heating voltage 6.3 V and anode voltage 150-300 V, and connect the deflection plates to the anode potential.

  Thermionic emission begins within just a few minutes of switching on the setup.
- Optimize the beam by varying the voltage to the Wehnelt cylinder.

5.2 Further deflection in an electrical field



Additionally required:

1 Commutator switch	504 49
1 Measuring resistor 100 kΩ	537 85

Note: Do not exceed an anode voltage of 250 V.

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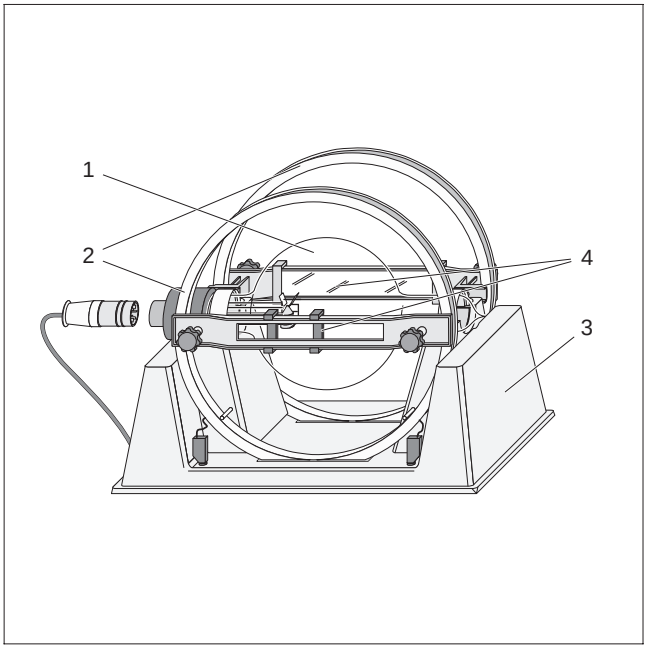
03/99-V5-Sel



Instruction Sheet 555 571

Fine beam tube (555 571)
Helmholtz coils with holder and measuring device (555 581)

1 Fine beam tube

2 Helmholtz coils

3 Holder

4 Measuring device

The fine beam tube (555 571) is used in conjunction with the Helmholtz coils with holder and measuring device (555 581) to investigate the deflection of electron beams in electrical and magnetic fields, particularly the determination of the specific electron charge e/m.

The electron-beam system of the fine beam tube consists of an indirectly heated cathode, a conical anode from which the electrons emerge straight up, and a Wehnelt cylinder for focusing the electron beam. A pair of plates is positioned directly behind the anode for electrostatic deflection of the electron beam.

The Helmholtz coils with holder and measuring device (555 581) allow you to put the fine beam tube into operation and enable generation of a homogeneous magnetic field perpendicular to the electron beam of the fine beam tube. The operating voltages are connected in a clearly understandable fashion via safety sockets in the connection panel, which are internally connected with the sockets for the Helmholtz coils and connected to the electron beam system via a permanently attached cable. The measuring device, consisting of one straight member with two slides and one straight member with mirror, allows you to determine the diameter of a circular electron beam.

Safety notes

Attention: The fine beam tube requires dangerous contact voltages of up to 300 V for accelerating the electrons. Other voltages that are connected with this dangerous contact voltage also present a contact hazard. Dangerous contact voltages are thus present at the connection panel of the stand and at the Helmholtz coils when the fine beam tube is in operation.

- Connect the connection panel only via safety connecting leads.
- Always be sure to switch off all power supplies before connecting and altering the experiment setup.
- Do not switch on the power supplies until you have finished assembling the circuit.
- Do not touch the experiment setup, particularly the Helmholtz coils, during operation.

Danger of implosion: the fine beam tube is an evacuated glass vessel with thin walls.

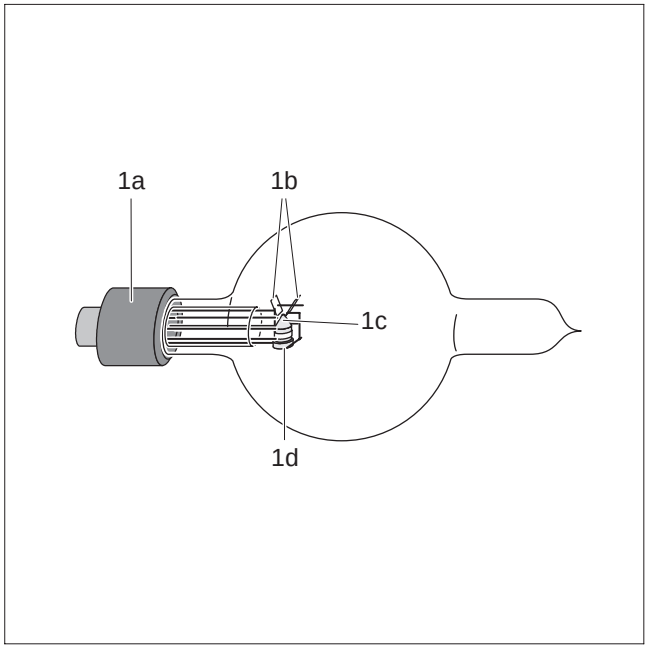
- Do not subject the fine beam tube to mechanical stresses.
- Use the fine beam tube only in the stand (555 581).
- Carefully connect the 6-pin plug of the stand to the base.

The fine beam tube can be destroyed by excessive voltages and currents, as well as by the wrong cathode temperatures.

- Do not exceed the operating parameters of the fine beam tube given in the technical data, particularly the maximum heating voltage of 6.3 V.

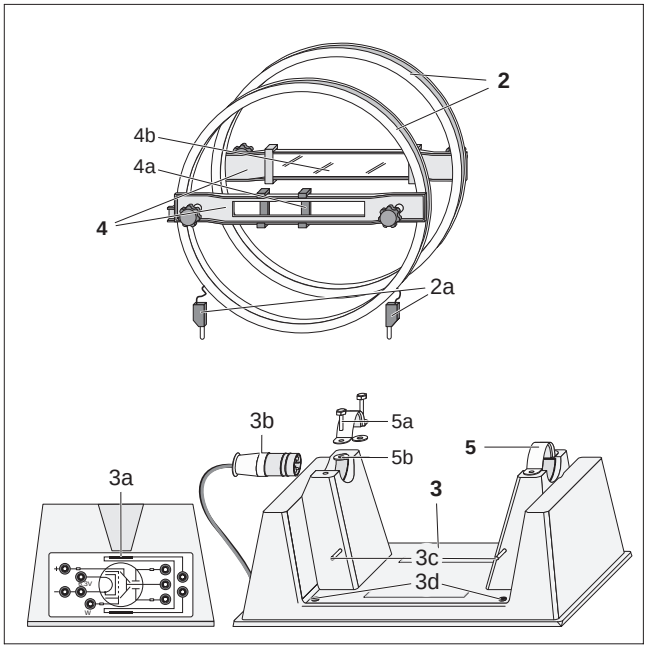
1 Scope of supply

1.1 Fine beam tube (557 571)



1 Fine beam tube
base (1a),
deflection plates (1b),
anode (1c),
cathode, Wehnelt cylinder (1d)

1.2 Helmholtz coils with holder and measuring device (555 581)



2 Pair of Helmholtz coils
4-mm plug (2a)

3 Holder
connection panel with diagram (3a), 6-pin plug (3b),
locking pins for Helmholtz coils (3c),
connection sockets for Helmholtz coils (3d)

4 Measuring device (catalog number: 555 59)
straight member with slides (4a), straight member with mirror (4b)

5 Retainer brackets
M4 screws (5a), washers (5b)

2 Technical data

2.1 Fine beam tube (557 571)

Glass bulb:

Gas filling:	hydrogen, approx. 1 Pa
Diameter:	16 cm

Glass base:

Connection:	6-pin

Electron beam system:

Heating voltage:	6.3 V
Heating current:	approx. 0.7-0.8 A
Anode voltage:	150-300 V DC
Wehnelt voltage:	±20 V
Plate voltage:	0-300 V DC

2.2 Helmholtz coils with holder and measuring device (555 581)

Pair of Helmholtz coils:

Number of turns:	130 per coil
Maximum coil current:	2 A (3 A transient)
Resistance:	approx. 2 Ω per coil
Coil radius:	150 mm
Coil spacing:	150 mm

Relationship between magnetic field B and coil current I:

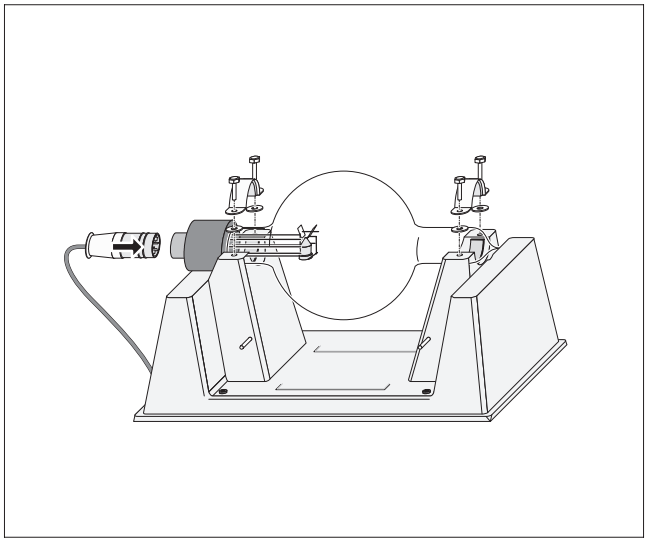
$$B = \mu_0 \cdot \left(\frac{4}{5}\right)^{\frac{3}{2}} \cdot \frac{n}{R} \cdot I$$

$\mu_0 = 4\pi \cdot 10^{-7} \frac{\text{Vs}}{\text{Am}}$: magnetic field constant

R: Coil radius
n: Number of turns = 130 per coil

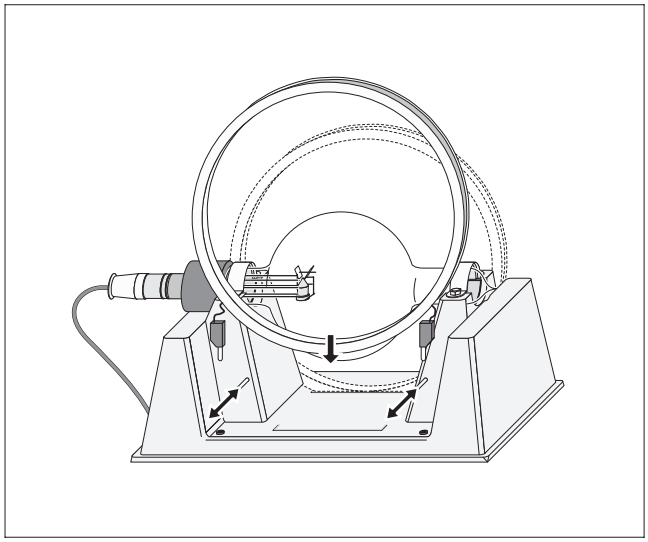
3 Assembly

3.1 Mounting the fine beam tube:



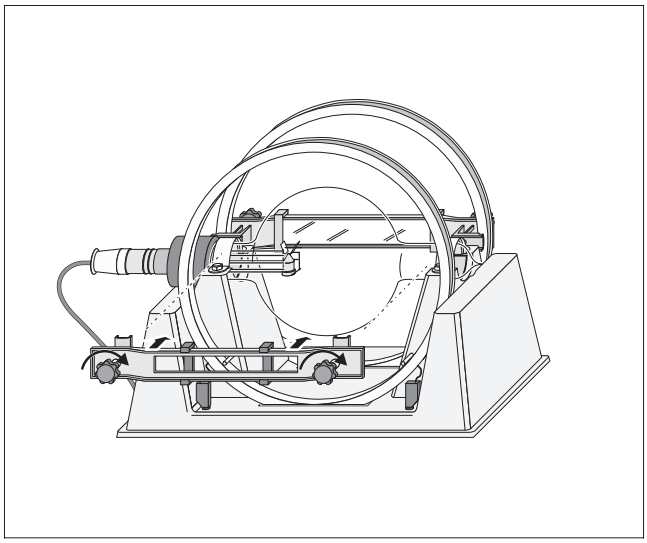
- Mount the fine beam tube so that the beam opening of the anode is pointing straight up.
- Alternately tighten the screws of the retainer brackets, being very careful to avoid one-sided mechanical stresses.
- Carefully connect the 6-pin plug to the glass base.

3.2 Mounting the Helmholtz coils:



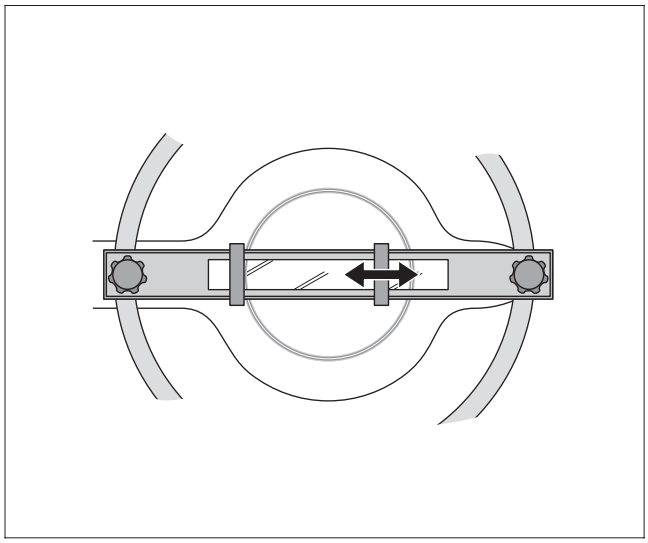
- Push the locking pins “forward”, mount the “back” Helmholtz coil and plug the 4-mm connector into the corresponding socket.
- Push the locking pins “backward”, and mount and connect the “front” Helmholtz coil.
- Set the pins in the middle position to hold both coils in place.

3.3 Attaching the measuring device



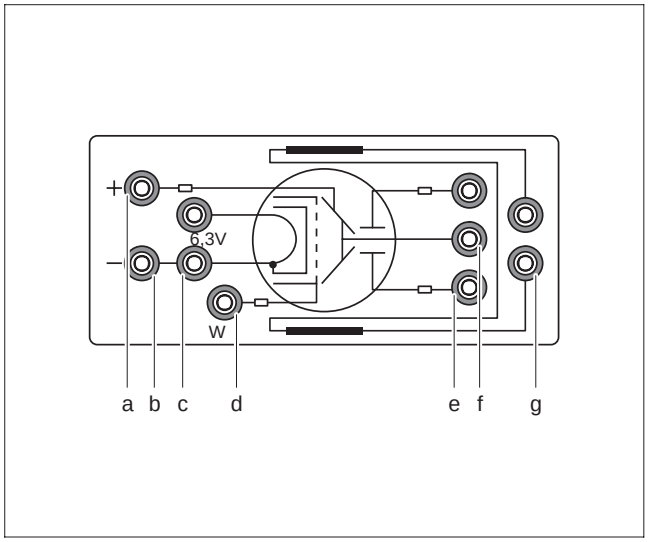
- Attach the straight member with mirror horizontally to the back Helmholtz coil and the member with two slides to the front Helmholtz coil.

3.4 Using the measuring device



- Move the left slide so that the inside edge, the mirror image and the beam aperture of the electron beam are in one line of sight.
- Move the right slide until the inside edge, mirror image and fine beam are in line.

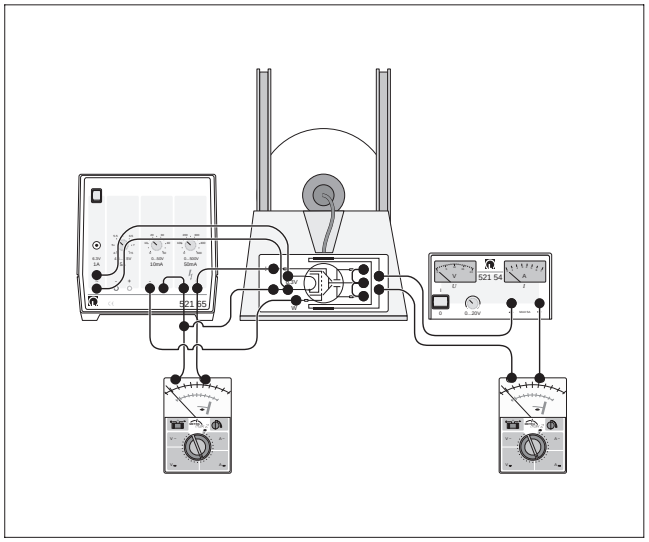
4 Socket assignments



a Anode
b Cathode
c Cathode heating
d Wehnelt cylinder
e Deflection plates
f Anode, for symmetrical adjustment of the deflection voltage
g Helmholtz coils

5 Operation

5.1 Determining e/m (deflection in a magnetic field)



Additionally required:

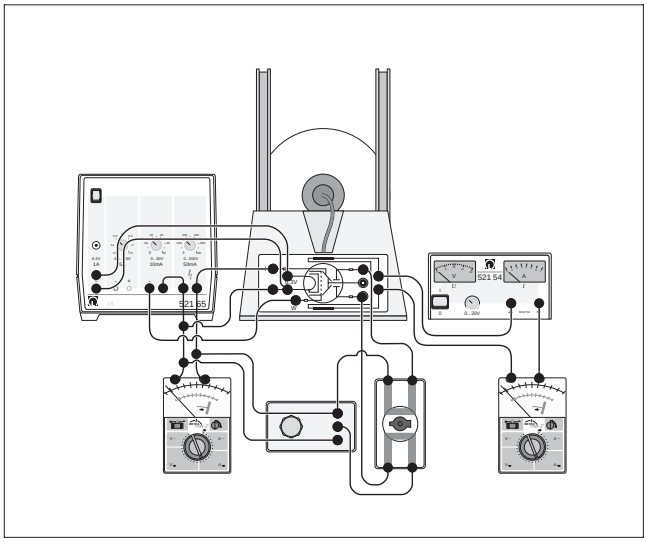
1 Tube power supply		521 65
1 Voltmeter, 300 V DC	e.g.	531 100
1 Stabilized power supply, 20 V, 3 A, DC	e.g.	521 54
1 Ammeter, 3 A DC	e.g.	531 100

− Apply the heating voltage 6.3 V and anode voltage 150-300 V, and connect the deflection plates to the anode potential.

  Thermionic emission begins within just a few minutes of switching on the setup.

− Optimize the beam by varying the voltage to the Wehnelt cylinder.

5.2 Further deflection in an electrical field



Additionally required:

1 Commutator switch	504 49
1 Measuring resistor 100 kΩ	537 85

Note: Do not exceed an anode voltage of 250 V.

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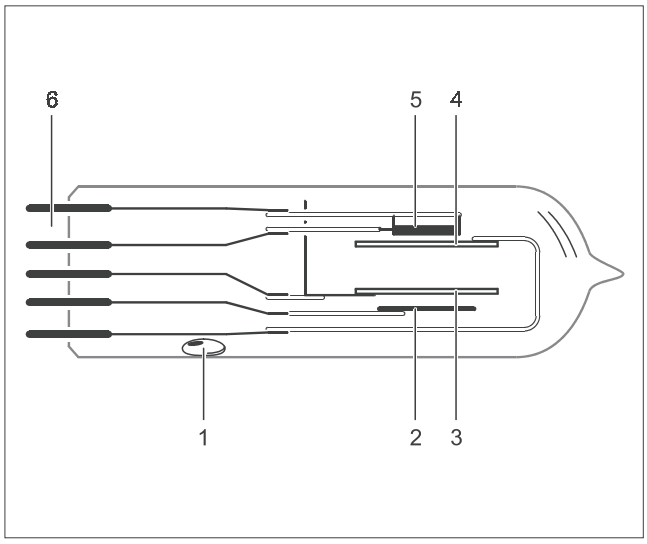
Franck-Hertz equipment

Lehr– und Didaktiksysteme
LD Didactic GmbH
Leyboldstrasse 1 · D-50354 Huerth

03/06-W97-Kem/Sel



Instruction sheet 555 854

Hg Franck-Hertz tube (555 854)

1 Mercury filling
2 Collector
3 Accelerating grid
4 Emitting grid
5 Cathode
6 Pin base

Safety notes

Danger of implosion: The Hg Franck-Hertz tube is a high-vacuum tube made of thin-walled glass filled with approx. 5 g of mercury.

- Do not expose the Hg Franck-Hertz tube to mechanical stress, and connect it only mounted in the socket for Hg Franck-Hertz tube (555 864 or 555 865).
- Treat the contact pins in the pin base with care, do not bend them, and be careful when inserting them in the socket.

Mercury released when the glass breaks is poisonous if inhaled. There is danger of cumulative effects.

- Avoid contact with the released substance.
- Collect released substance, e.g. with the mercury adsorbent (306 83), and dispose of it according to applicable regulations. Must not be introduced into the sewerage system.
- Do not inhale vapour or aerosols, and air closed rooms.

The Hg Franck-Hertz tube is heated during operation:

- Allow the Hg Franck-Hertz tube to cool down before taking it out of the electric oven.
- Make sure that the maximum temperature is not exceeded by controlling the heating with the Franck-Hertz supply unit or another control instrument.

1 Description

The Hg Franck-Hertz tube is a vacuum tube with an indirectly heated cathode, an emitting grid, an anode grid, and a collector. It contains a drop of mercury, which evaporates when the tube is heated. This arrangement makes it possible to carry out the experiment of J. Franck and G. Hertz, which demonstrates the discrete energy transfer in collisions of free electrons with mercury atoms. It is also possible to determine the excitation energy of the atoms.

2 Technical data

Mercury filling:	approx. 5 g
Excitation energy of the Hg atoms:	4.9 eV
Hg vapour pressure:	12 hPa at 180°C
Operating temperature:	approx. 180°C
Maximum temperature:	200°C continuously 220°C for short periods
Cathode heating:	4 V* / 0.5 A (AC or DC) indirectly

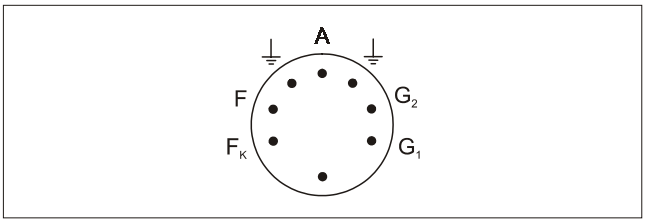
* A voltage of 6.3 V can be applied because of a series resistor in the socket (555 864 or 555 865)

Emitting grid voltage:	approx. 3 V DC
Accelerating voltage:	0 to 30 V DC
Countervoltage at collector:	approx. -1.5 V DC
Pin base:	9-pin
Dimensions:	10 cm x 2.8 cm dia.

3 Accessories

1 socket for Hg Franck-Hertz tube, with DIN connector (555 864)
or
1 socket for Hg Franck-Hertz tube, with 4 mm plug (555 865)

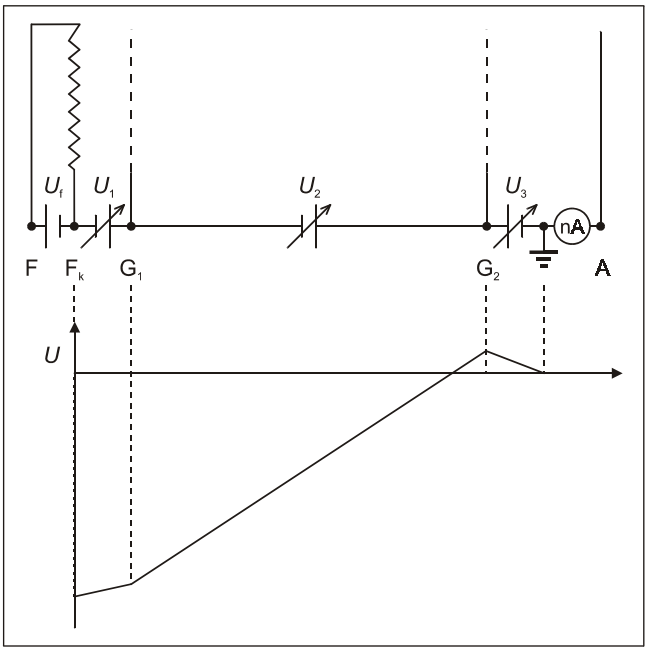
4 Pin configuration



View on pin base

G1	Emitting grid
G2	Accelerating grid
⏚	Reference pins, grounded when the tube is connected to the Frank-Hertz supply unit (555 880)
A	Collector
F, Fk	Cathode

5 Principle of measurement



Cathode heating: U_f = 6.3 V AC/ DC, floating

Emitting grid voltage: U_1 = 0 ... 5.0 V DC, floating

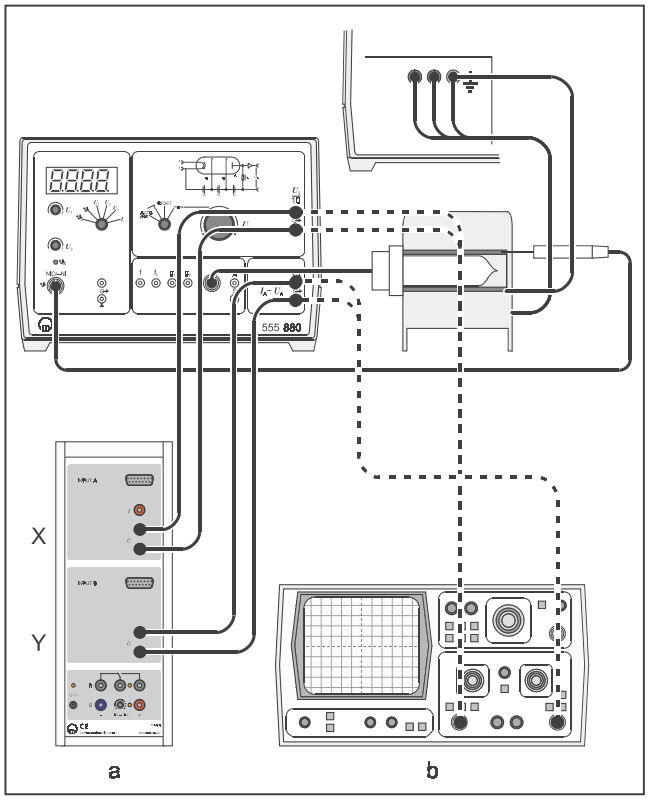
Accelerating voltage: U_2 = 0 ... 30.0 V DC, floating

Countervoltage: U_3 = 0 ... 5.0 V DC, floating

For a sufficient mercury vapour pressure, the Hg Franck-Hertz tube has to be heated to approx. 180° C.

The collector current I is measured as a function of the accelerating voltage U_2 at optimized voltages U_1 and U_3.

6 Operation



additionally recommended:

1 Franck-Hertz supply unit	555 880
1 socket for Hg Franck-Hertz tube, with DIN connector	555 864
1 temperature sensor NiCr-Ni	666 193
1 electric oven, 200 W, 230 V	555 81
or	
1 electric oven, 200 W, 115 V	555 82
1 two-channel oscilloscope	575 211
or	
1 Sensor-CASSY	524 010
1 CASSY Lab	524 200

Working as a temperature measuring and control device, the Franck-Hertz supply unit controls the electric oven. It also supplies the required voltages, namely the cathode heating voltage, the emitting grid voltage, the accelerating voltage, and the countervoltage, and it contains a nanoammeter for measuring the collector current.

Remark:

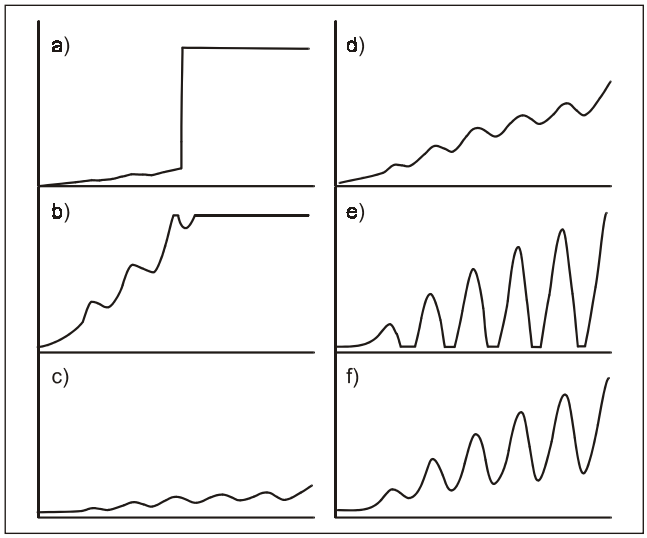
In the cold Hg Franck-Hertz tube, metallic mercury can cause a short between the electrodes:

- Apply voltages to the Hg Franck-Hertz tube only when the operating temperature has been reached.

Recording the Hertz curve:

- Adjust the emitting grid voltage U_1 = 3 V and the counter-voltage U_3 = 1.5 V, and record the Franck-Hertz curve.

Optimizing the Franck-Hertz curve:



a) Optimizing ϑ

If the Franck-Hertz curve exhibits a step-like rise (a) and a bright blue luminescence is observed in the Franck-Hertz tube through the insert opening of the electric oven:

- Switch the voltages at the Hg Franck-Hertz tube off immediately, and wait until the operating temperature is reached.
- If necessary, enhance the operating temperature (e.g. by 5 °C), and wait some minutes until the new thermal equilibrium is established.

b) Optimizing U_1 (a higher voltage U_1 leads to a higher emission current of the electrons).

If the Franck-Hertz curve rises too steeply and is cut off at the top already below U_2 = 30 V (b):

- Reduce U_1 until the slope of the curve corresponds to (d).

If the Franck-Hertz curve is too flat, i.e. the collector current I_A remains below 5 nA in the entire range (c):

- Increase U_1 (max. 4.8 V) until the slope of the curve corresponds to (d).

If the Franck-Hertz curve remains flat despite an increase of U_1:

- Reduce the setpoint ϑ_S for the oven temperature.

c) Optimizing U_3 (a higher counter voltage U_3 leads to more pronounced maxima and minima of the Franck-Hertz curve; at the same time the overall collector current is reduced):

If the maxima and minima of the Franck-Hertz curve are weakly pronounced (d):

- alternately increase the counter voltage U_3 (maximally 4.5 V) and then the emitting grid voltage U_1 until the shape (f) is reached.

If the minima of the Franck-Hertz curve are “cut off” at the bottom (e):

- alternately decrease the counter voltage U_3 (maximally 4.5 V) and then the emitting grid voltage U_1 until the shape (f) is reached.

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This operating unit provides all voltages necessary for performing the Franck-Hertz experiment and contains a high-sensitivity DC amplifier for measuring the electron stream collected at the target electrode. It can be used equally well for performing the experiment with mercury vapor or with neon gas filled tubes. Using this unit considerably simplifies the experimental setup. It requires only five connections to the socket of a neon gas filled Franck-Hertz tube, or four connections to the front panel of a Franck-Hertz tube with mercury vapor. Then the associated measurement devices are connected, completing the experimental setup.

The operating unit for the Franck-Hertz experiment provides the following:

1. The accelerating voltage U_B (red jack): a regulated DC voltage continuously adjustable from 0 V to 80 V ("U_B" toggle switch in "Man" position).

2. The heater voltage U_H (green jack): a DC voltage from 4 V to 12 V for the filament of the indirectly heated oxide-coated cathode. This makes it possible to adjust the heater current from 180 to 400 mA.

3. The control voltage (brown jack): a fixed voltage of 9 V DC; required for operation of the Franck-Hertz tube with neon gas filling.

4. The reverse bias U_G: a voltage adjustable between –1.2 V and –10 V for protecting the target electrode and controlling the Franck-Hertz signal.

The unit also provides the following for displaying the Franck-Hertz signal on the oscilloscope:

5. A saw-tooth accelerating voltage U_B with a voltage level adjustable from 0 Vpp to 80 Vpp ("U_B" toggle switch in Ramp/50 Hz position). The deflection frequency is fixed at 50 Hz.

6. The necessary deflection voltage (half-wave voltage produced by half-wave rectification) for observing the Franck-Hertz curve with the oscilloscope. The amplitude of the deflection voltage is reduced to one tenth of the selected accelerating voltage (U_B/10).

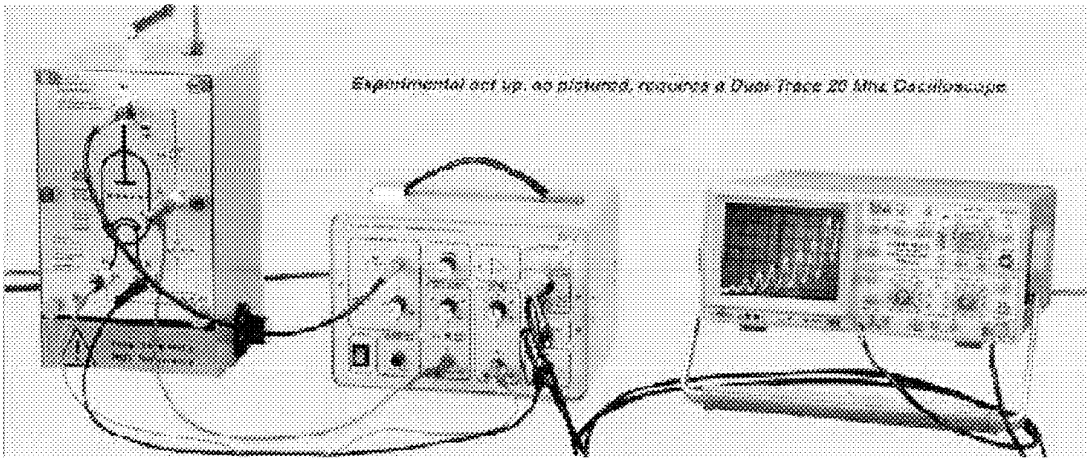
The DC amplifier consists of two cascaded operational amplifiers (OP), the first of which is wired as an electrometer amplifier. The measurement current is supplied to the non-inverting input of the first OP. The input resistance is 680 kOhm. The amplification of the Franck-Hertz signal can be adjusted using a negative feedback potentiometer ("Amplitude" control). In the second cascaded OP the signal is further amplified and inverted. The measurement voltage at the output is proportional to the target current. A measurement voltage of 1 V corresponds to an electron current of approximately 10 µA at minimum amplification ("Amplitude" knob all the way to the left), and an electron current of approximately 10 nA at maximum amplification ("Amplitude" knob all the way to the right). An ordinary commercial voltmeter with a range of 10 V can be used as a measurement instrument. It is not necessary to adjust the instrument. The measurement voltage can be loaded to 10 mA and is short-circuit protected.

Experimental Setup

Franck-Hertz Experiment with Mercury Filling

The figure below shows the experimental setup for performing the Franck-Hertz experiment with mercury filling, consisting of:

1. Franck-Hertz tube with mercury filling on front panel
2. Oven, thermostatically controlled, 110V mains (available in 220V, special order)
3. Operating unit for Franck-Hertz experiment, 110V mains (available in 220V, special order)
4. Dual-channel oscilloscope
5. X-Y recorder



Procedure:

1. Connect the various devices as shown in the figure. Do NOT connect the recorder and the oscilloscope at the same time. The oscilloscope is used first in order to adjust for a clear curve. The X-Y recorder is then used to produce a curve on paper.

Operating Unit	Socket/Tube	Oscilloscope	Recorder (alternative)	Voltmeter	Comments
PE	PE				for neon filling only
K	K/Cathode			- Input	
H	H/Heater				
A	A/Anode			+ Input	
Control Grid 9 V/10 mA	Control Grid				for neon filling only
M Signal Franck-Hertz Signal Output	BNC (Tube)	Ch. 1 (Y input)	Y input		
U_B/10 Output		Ch. 2 (X input)	X input		

Preliminary Adjustments

2. Set the oven to the desired temperature (e.g., 200 ºC). The data sheet supplied with the tube can be used as a guideline.
3. Before turning the unit on, turn the controls for "Heater", "Acceleration", and "Amplitude" all the way to the left stops. Set the control for "Reverse Bias" to the center position.
4. Turn the unit on with the illuminated green switch (bottom left).
5. Set the toggle switch "Man, Ramp/50 Hz" to "Ramp".
6. Connect the unit's Franck-Hertz signal output to the oscilloscope's Y input (Ch 1), and the $U_B/10$ output to the X input (Ch 2).
7. Set the oscilloscope for X-Y operation and set Ch 1 and Ch 2 for an amplification of 1 V/cm in DC mode.
8. Turn on the oscilloscope.
9. Rotate the oscilloscope's X and Y position controls to move the beam to the lower left corner of the screen.

Adjustments:

a) Now, carefully adjust the heater voltage to a value of approximately 8 V.
b) Bring the accelerating voltage to a value of approximately 40 V to 50 V.
c) Rotating the "Amplitude" control increases the amplitude of the signal. Once the oven has reached the desired temperature, one can observe the gradual appearance of the Franck-Hertz curve on the oscilloscope screen.
d) Vary the reverse bias such that a curve with well-defined minima and maxima appears.

By increasing the accelerating voltage to a value of approximately 80 V and slightly changing the other parameters (including the oven temperature if necessary), one can observe the Franck-Hertz curve on the oscilloscope screen, which proceeds from the bottom left to the top right and shows up to 13 pronounced maxima or minima (Fig. 2). The accelerating voltage must not be increased so far that an independent discharge occurs in the tube, since collision ionization disrupts the curve.

The method described is a general adjustment procedure. Since Franck-Hertz tubes are manufactured by hand, the optimal parameters vary widely from tube to tube. The data sheet delivered with the tube provides a guideline for good values.

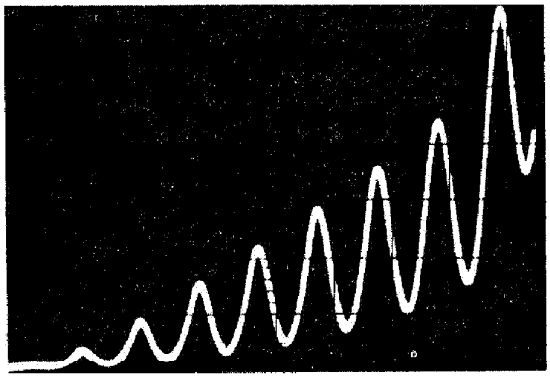


Fig. 2 Oscilloscope image of the Franck-Hertz curve

Precise Analysis of the Franck-Hertz Curve:

The precise analysis of the Franck-Hertz curve additionally uses an X-Y recorder and a digital voltmeter. It is not absolutely necessary to measure the absolute value of the thermionic current for this purpose. You should first set up a Franck-Hertz curve on the oscilloscope screen that has well-defined maxima and minima.

Procedure:

a) Set the "Man/Ramp 50 Hz" toggle switch to "Man".
b) Rotate the control for the accelerating voltage to the left stop (U_B = 0V).
c) Also connect the digital voltmeter to the unit's "A" and "K" jacks.
d) By rotating the control for the accelerating voltage to the right stop, you can measure a maximum accelerating voltage of approximately 80 V. Afterwards, rotate the U_B control back to the left stop.
e) Remove the measurement cables from the oscilloscope's X and Y inputs and replace them with 4 mm cables connected to the corresponding inputs of the X-Y recorder.
f) Turn the X-Y recorder on and set both its axes to an amplification of 1 V/cm.

Note: The accelerating voltage at the signal output (recorder signal) is reduced by a factor of 10. However, the digital voltmeter measures the full accelerating voltage between the "A" and "K" connections.

g) You can now vary the amplification at the recorder so as to obtain a Franck-Hertz curve that fills the sheet of paper.

h) You can now record a Franck-Hertz curve (Fig. 3) by slowly and steadily raising the accelerating voltage U_B, and determine the exact positions of the maxima and minima with the digital voltmeter.

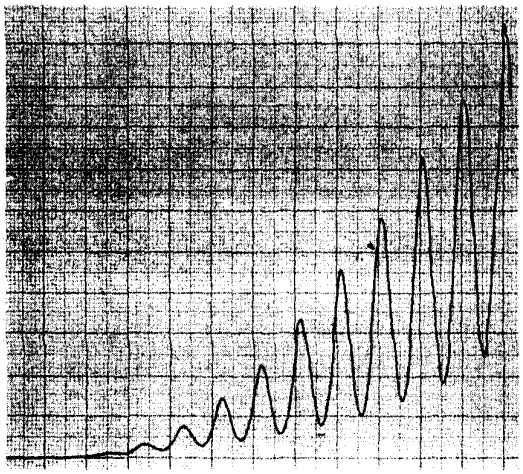


Fig. 3 Recorder image of the Franck-Hertz curve

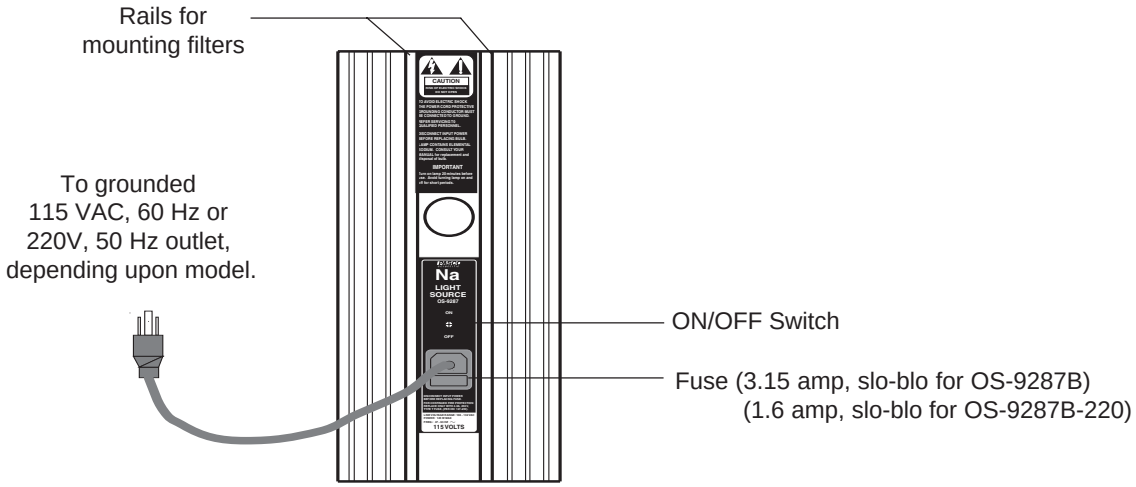
Franck-Hertz Experiment with Neon Filling

In addition to the connections reproduced in Fig. 1, the control electrode for the neon Franck-Hertz tube must also be connected to the corresponding jack on the unit. Setup follows the same sequence as in the case of the mercury Franck-Hertz curve; however, only three maxima are possible here.

Michelson-Morley and diffracton experiments equipment

Instruction Sheet for the PASCO Model OS-9287B

Sodium Light Source



Introduction

The PASCO scientific Model OS-9287B Low Pressure Sodium Light Source provides 6 candela/cm^2, with better than 99.5% of the visible output in the 5889 and 5895 angstrom spectral lines. The light source comes with a built-in power supply so the unit can be powered from a standard 115 VAC, 60 Hz or 220 VAC, 50 Hz outlet, depending upon the model. Cooling fins and air vents on the sturdy aluminum case ensure cool, safe operation. The rails on the front and rear of the case allow easy mounting of standard 2-inch by 2-inch filters.

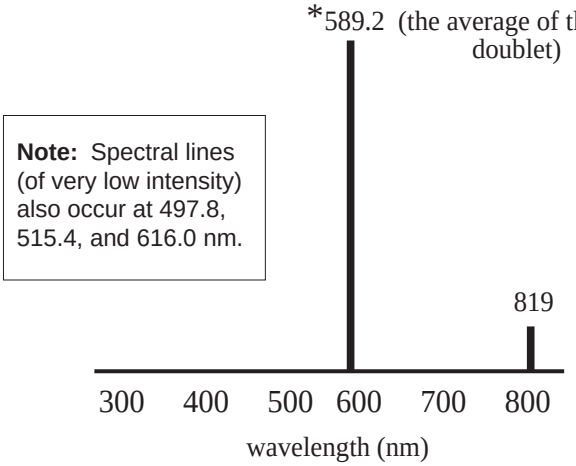
To operate the light source, simply plug it into a grounded 115 VAC outlet; then flip the switch on the front of the light source to On. Allow approximately 20 minutes warm-up time. (The first time you use your light source, you will need to install the sodium lamp. See the following page for initial setup instructions.)

Important Note—For maximum lamp life:

1. Always operate the light source in its upright position. Operation in other orientations will severely reduce the life of the lamp.

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

The spectrum for the lamp is shown below. Better than 99.5% of the visible output is in the sodium doublet at 5889* and 5895* angstroms. Slight impurities (1% neon and argon) are added to the sodium gas to improve operating efficiency. Because of this, the lamp is not recommended for use with instruments having a resolving power in excess of 1 part in 10^4. The sodium pressure in the lamp is 5 microns Hg.



Note: Spectral lines (of very low intensity) also occur at 497.8, 515.4, and 616.0 nm.

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This instruction sheet edited by: Dave Griffith

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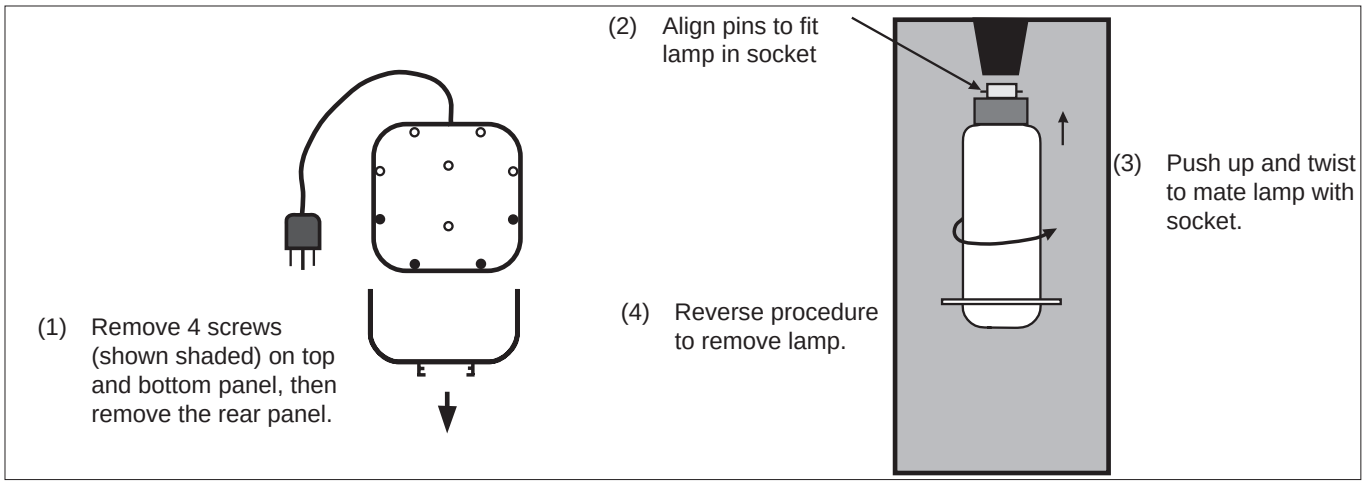
Initial Setup

Before using the Light Source for the first time, you will need to install the lamp. To do this, just follow the numbered instructions shown below.

➤**CAUTION--HIGH VOLTAGE:** Do not open the light source with the unit plugged in.



CAUTION

RISK OF ELECTRIC SHOCK DO NOT OPEN

CAUTION:
TO PREVENT THE RISK OF ELECTRIC SHOCK, DO NOT REMOVE BACK COVER. NO USER SERVICEABLE PARTS INSIDE. REFER SERVICING TO QUALIFIED SERVICE PERSONNEL.

The lightning flash with arrowhead, within an equilateral triangle, is intended to alert the user of the presence of uninsulated "dangerous voltage" within the product's enclosure that may be of sufficient magnitude to constitute a risk of electric shock to persons.

The exclamation point within an equilateral triangle is intended to alert the user of the presence of important operating and maintenance (servicing) instructions in the literature accompanying the appliance.

Maintenance

The light source lamp, when used correctly (see the note on the front panel of the unit), can be expected to provide 14,000+ hours of trouble free operation. However, if the light at any time fails to come on, first check the fuse on the front of the light source case. If the fuse is not blown, you may need to replace the lamp. In rare cases, the problem may be with the ballast. However, ballast replacement should be performed only by experienced personnel. If the fuse is intact and replacing the bulb does not restore operation, we recommend you return the unit to PASCO scientific for repair.

Only the following replacement parts should be used:

Item	PASCO Part #
Fuse (3.15 amp)	530-033
Fuse (1.6 amp)	530-034
Lamp	526-034
110 volt Ballast	322-042
220 volt Ballast	322-05440
220 volt Ignitor	550-05441

Replacing the Sodium Lamp:

> **Caution—High Voltage:** Do not open the light source with the unit plugged in.

1. Unplug the light source, and allow several minutes for the sodium lamp to cool.
2. Remove the rear panel and replace the lamp as shown in the Initial Setup instructions above.
3. Replace the rear panel.

> **Caution—Disposing of the Sodium Lamp:** The sodium lamp contains a small quantity of metallic sodium which produces heat when dampened. To dispose of a used lamp, wrap the lamp in several rolls of dry paper, then place it in a dry container. Then, in a dry atmosphere, break the lamp carefully into smaller pieces. Finally, stand back and fill the container with water. Within a few minutes the metallic sodium will be deactivated. Dispose of the lamp pieces as you would any broken glass.

> **Note:** If additional maintenance is required, it should be performed only by qualified personnel (see the schematic on the following page.)

Other PASCO Spectral Equipment

PASCO scientific offers a variety of spectral light sources, and a precision student spectrometer for accurate spectral measurements in the student lab. For more information, check our catalog, or call toll-free at 1-800-772-8700.

Limited Warranty

PASCO scientific warrants this product to be free from defects in materials and workmanship for a period of one year from the date of shipment to the customer. PASCO will repair or replace, at its option, any part of the product which is deemed to be defective in material or workmanship. This warranty does not cover damage to the product caused by abuse or improper use. Determination of whether a product failure is the result of a manufacturing defect or improper use by the customer shall be made solely by PASC0 scientific. Responsibility for the return of equipment for warranty repair belongs to the customer. Equipment must be properly packed to prevent damage and shipped postage or freight prepaid. (Damage caused by improper packing of the equipment for return shipment will not be covered by the warranty.) Shipping costs for returning the equipment, after repair, will be paid by PASCO scientific.

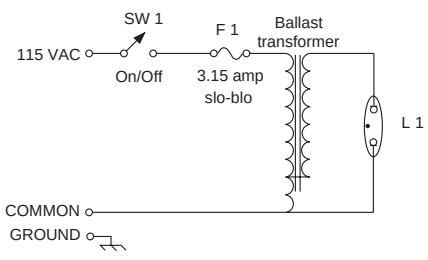
Equipment Return

Should this product have to be returned to PASCO scientific, for whatever reason, notify PASCO scientific by letter or phone BEFORE returning the product. Upon notification, the return authorization and shipping instructions will be promptly issued.

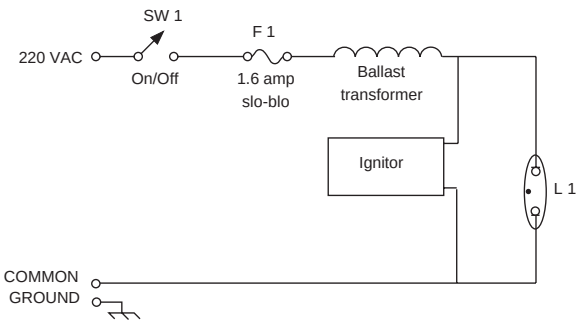
> NOTE: NO EQUIPMENT WILL BE ACCEPTED FOR RETURN WITHOUT AN AUTHORIZATION.

Schematic

115V



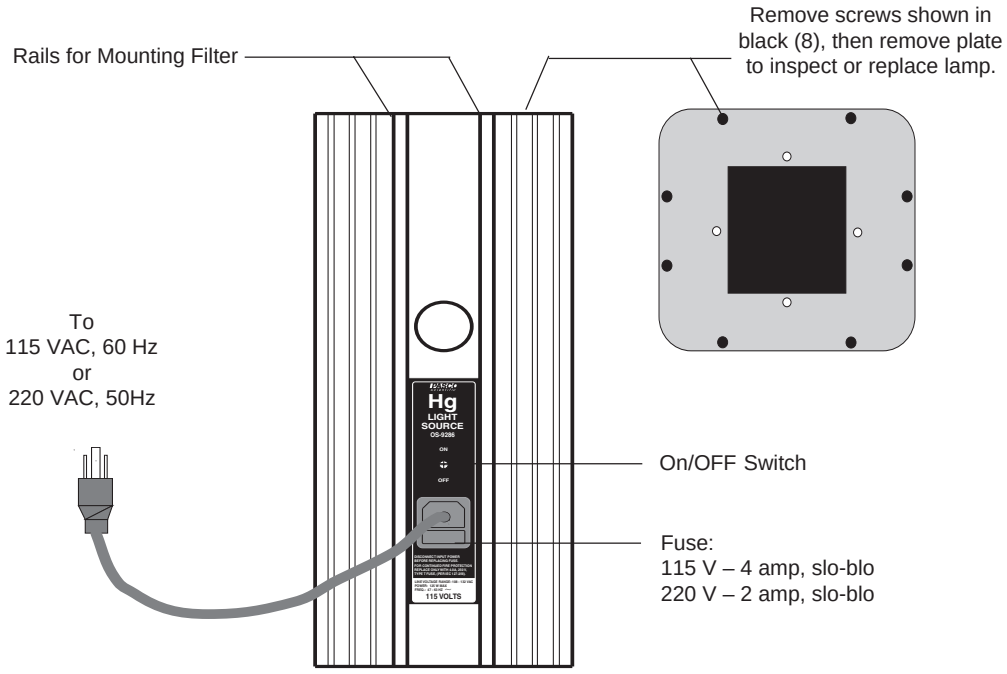
220V



Notes:

Instruction Sheet
for the PASCO
Model OS-9286A

MERCURY VAPOR LIGHT SOURCE



Introduction

The PASCO scientific Model OS-9286A Mercury Vapor Light Source provides approximately 3,000 lumens of light in the mercury spectrum. The 100 watt light source comes ready to use, with a built-in power supply so the unit can be powered from a standard 115 VAC, 60 Hz outlet (OS-9286A-220 is powered from a 220 VAC, 50 Hz outlet). Cooling fins and air vents on the sturdy aluminum case ensure cool, safe operation. In addition, rails on the front and rear of the case can be used for mounting standard 2-inch by 2-inch filters, so that monochromatic light can be obtained.

➤ **Note**: For maximum life of the mercury vapor lamp:

① Always operate the light source in its upright position.

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

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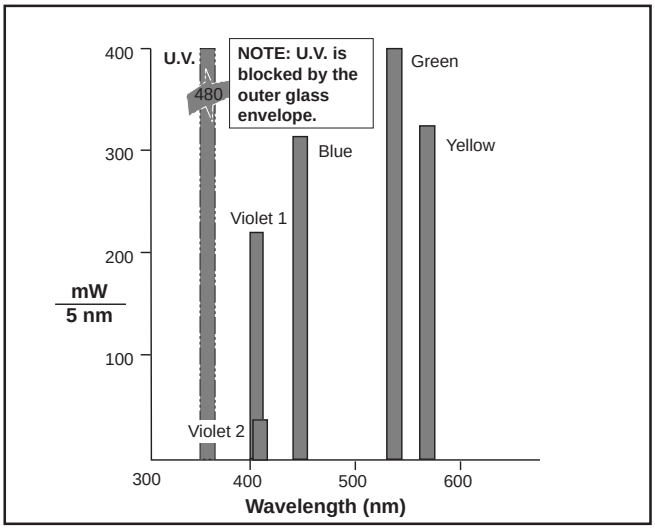


Spectral Power Distribution per 1000 Lumens

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

Wavelength of the Mercury Spectral Lines

All values except wavelength for yellow line are from *Handbook of Chemistry and Physics, 46th ed*. The wavelength of the yellow was determined experimentally using a 600 line/mm grating.

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

To Operate the Light Source:

Simply plug it into a standard, grounded, 115 VAC (or 220VAC) outlet; then flip the switch on the front of the light source to ON.

➤**CAUTION:** The outer glass tube of the mercury vapor lamp blocks harmful ultraviolet radiation produced by the lamp. *If the outer tube is cracked or broken, this radiation can cause severe skin burn and produce eye inflammation.* Regularly inspect the outer tube for cracks, especially if the light source has received a significant jolt. *If the glass bulb is broken, immediately turn lamp off and remove it to avoid possible injury.* Replace Bulb prior to next use.

CAUTION

RISK OF ELECTRIC SHOCK DO NOT OPEN

CAUTION:
TO PREVENT THE RISK OF ELECTRIC SHOCK, DO NOT REMOVE COVER ON UNIT. NO USER SERVICEABLE PARTS INSIDE. REFER SERVICING TO QUALIFIED SERVICE PERSONNEL.

The lightning flash with arrowhead, within an equilateral triangle, is intended to alert the user of the presence of uninsulated "dangerous voltage" within the product's enclosure that may be of sufficient magnitude to constitute a risk of electric shock to persons.

The exclamation point within an equilateral triangle is intended to alert the user of the presence of important operating and maintenance (servicing) instructions in the literature accompanying the appliance.

Maintenance

The light source lamp can be expected to provide 24,000+ hours of trouble free operation. However, if the light at any time fails to come on, first check the fuse on the front of the light source case. If the fuse is not blown, you may need to replace the lamp. In rare cases, the problem may be with the ballast. However, ballast replacement should be performed only by experienced personnel. If the fuse is intact and replacing the bulb does not restore operation, we recommend you return the unit to PASCO scientific for repair.

➤***CAUTION—HIGH VOLTAGE:*** *Do not open the light source with the unit plugged in.*

To Replace the Mercury Vapor Lamp:

① Unplug the light source. Allow 10 to 15 minutes for the lamp to cool.

② Unscrew the eight screws that attach the top plate of the light source and remove the top plate.

③ Using a glove or several folds of thick cloth to protect your hand, unscrew the lamp. Discard it as you would any broken glass.

④ Replace the lamp and the top plate of the light source.

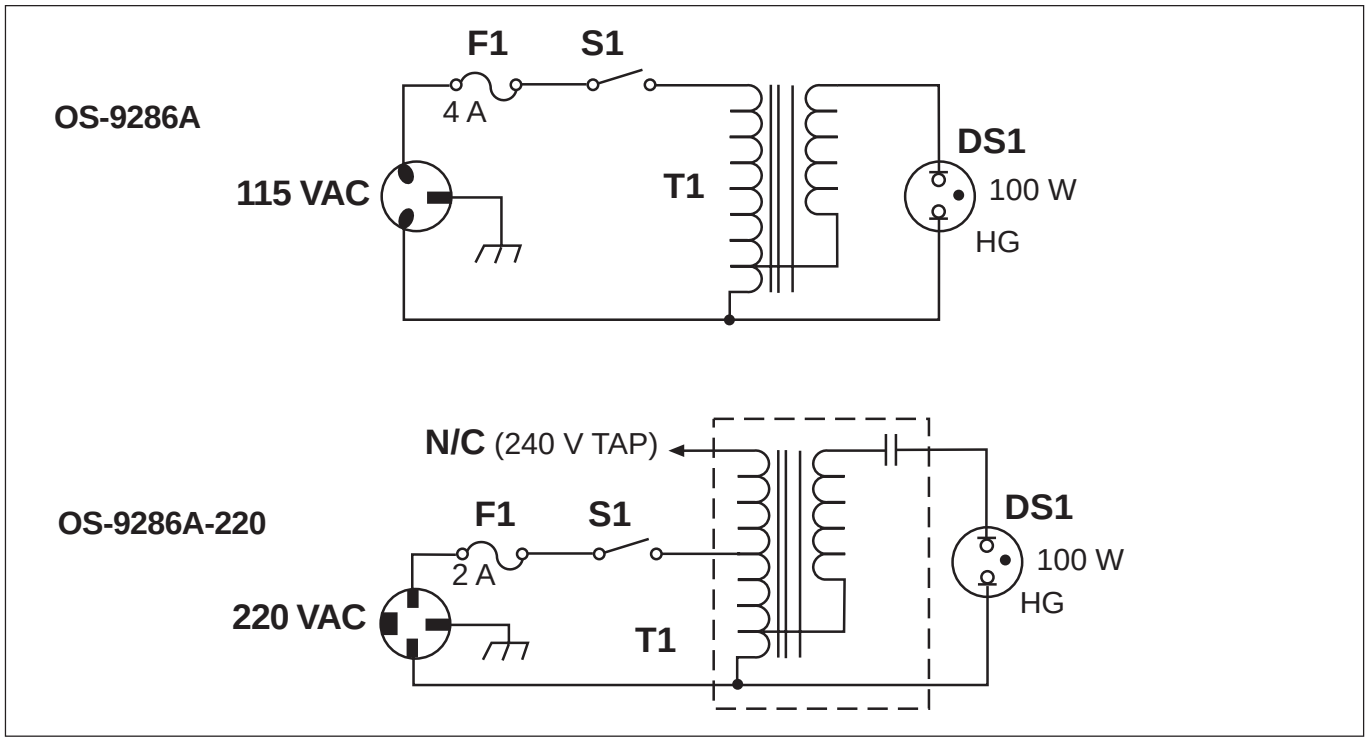
Replacement Parts

Only the following replacement parts should be used:

Description	Pasco #
OS-9286A	
Hg Lamp GE HR100A38	526-018
Hg Lamp Ballast	322-019
Fuse (5x20) 4 amp, slo-blo	530-035
OS-9286A-220	
Hg Lamp GE HR100A38	526-018
Hg Lamp Ballast	322-028
Fuse (5x20) 2 amp, slo-blo	530-036

Other PASCO Spectral Equipment

PASCO scientific offers a variety of student spectral light sources, and a precision student spectrometer for accurate spectral measurements in the student lab. For more information, check the current PASCO catalog, or call toll-free at 1-800-772-8700. Outside the United States call 1-916-786-3800.



Schematic

Warranty and Equipment Return

Limited Warranty

PASCO scientific warrants this product to be free from defects in materials and workmanship for a period of one year from the date of shipment to the customer. PASCO will repair or replace, at its option, any part of the product which is deemed to be defective in material or workmanship. This warranty does not cover damage to the product caused by abuse or improper use. Determination of whether a product failure is the result of a manufacturing defect or improper use by the customer shall be made solely by PASCO scientific. Responsibility for the return of equipment for warranty repair belongs to the customer. Equipment must be properly packed to prevent damage and shipped postage or freight prepaid. (Damage caused by improper packing of the equipment for return shipment will not be covered by the warranty.) Shipping costs for returning the equipment, after repair, will be paid by PASCO scientific.

Equipment Return

Should this product have to be returned to PASCO scientific, for whatever reason, notify PASCO scientific by letter or phone BEFORE returning the product. Upon notification, the return authorization and shipping instructions will be promptly issued.

NOTE:
NO EQUIPMENT WILL BE ACCEPTED FOR RETURN WITHOUT AN AUTHORIZATION.

When returning equipment for repair, the units must be packed properly. Carriers will not accept responsibility for damage caused by improper packing. To be certain the unit will not be damaged in shipment, observe the following rules:

① The carton must be strong enough for the item shipped.

② Make certain there is at least two inches of packing material between any point on the apparatus and the inside walls of the carton.

③ Make certain that the packing material can not shift in the box, or become compressed, thus letting the instrument come in contact with the edge of the box.

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Photoelectric effect equipment

Introduction

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

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

The relationship between the classical and quantum theories for the emission of light can be investigated using the PASCO scientific h/e Apparatus. Using the Apparatus in combination with the PASCO Mercury Vapor Light Source (Model OS-9286) allows an accurate determination of the h/e ratio and thus a determination of h, Planck's constant.

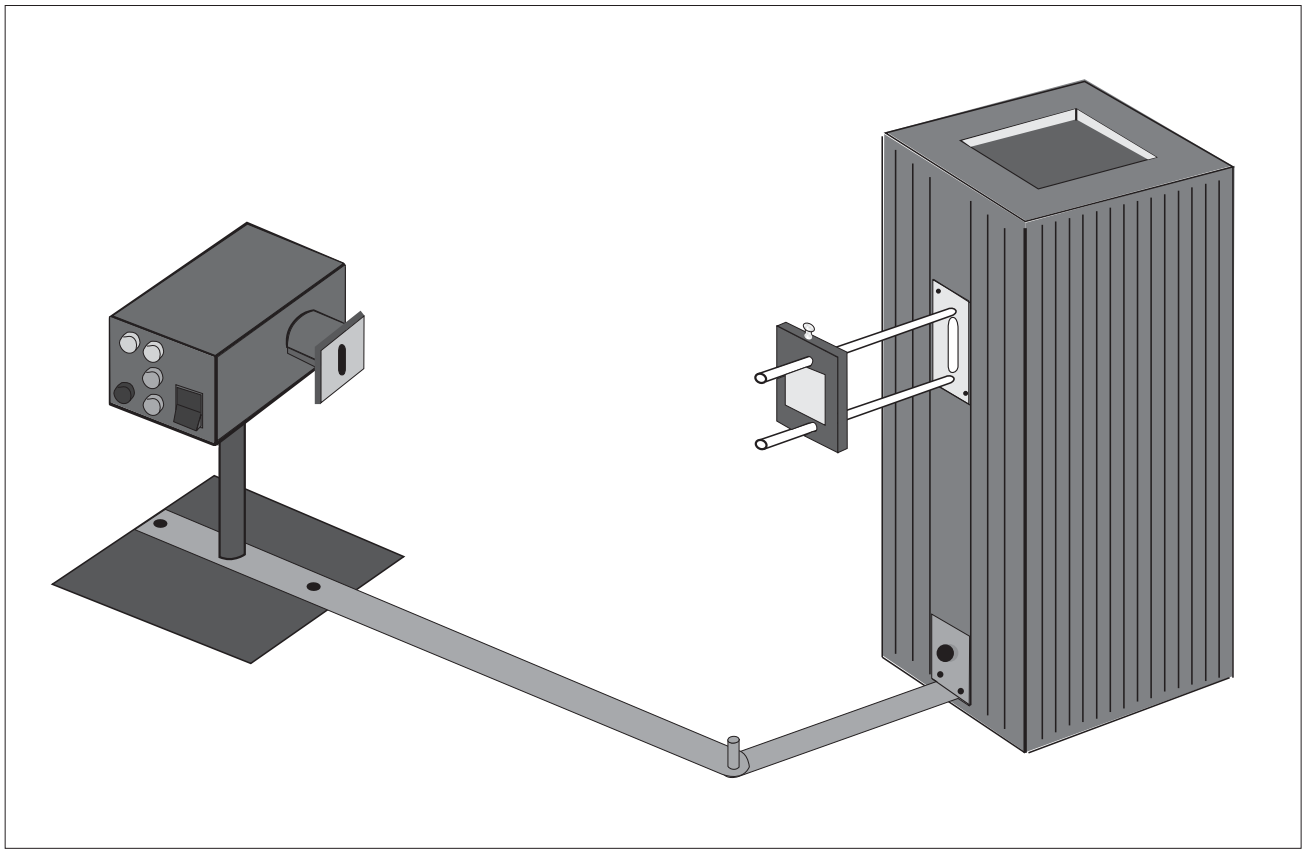


Figure 1. The h/e Apparatus Shown With the Accessory Kit and Mercury Vapor Light Source

Background Theory

Planck's Quantum Theory

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

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

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

$$E = h\nu$$

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

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

The Photoelectric Effect

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

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

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

The h/e Experiment

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

$$KE_{max} = Ve$$

Therefore, using Einstein's equation,

$$h\nu = Ve + W_O$$

When solved for V, the equation becomes:

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

If we plot V vs ν for different frequencies of light, the graph will look like Figure 2. The V intercept is equal to $-W_O/e$ and the slope is h/e. Coupling our experimental determination of the ratio h/e with the accepted value for e, 1.602×10^{-19} coulombs, we can determine Planck's constant, h.

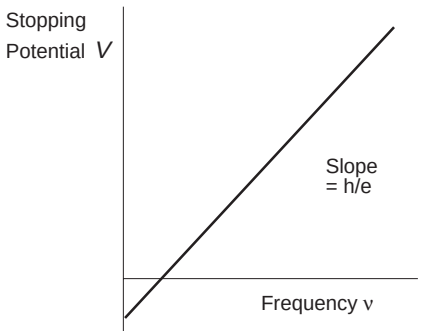


Figure 2. The graph of V vs. ν

***NOTE:** In experiments with the PASCO h/e Apparatus the stopping potential is measured directly, rather than by monitoring the photoelectric current. See the *Theory of Operation* in the Technical Information section of the manual for details.

Equipment and Setup

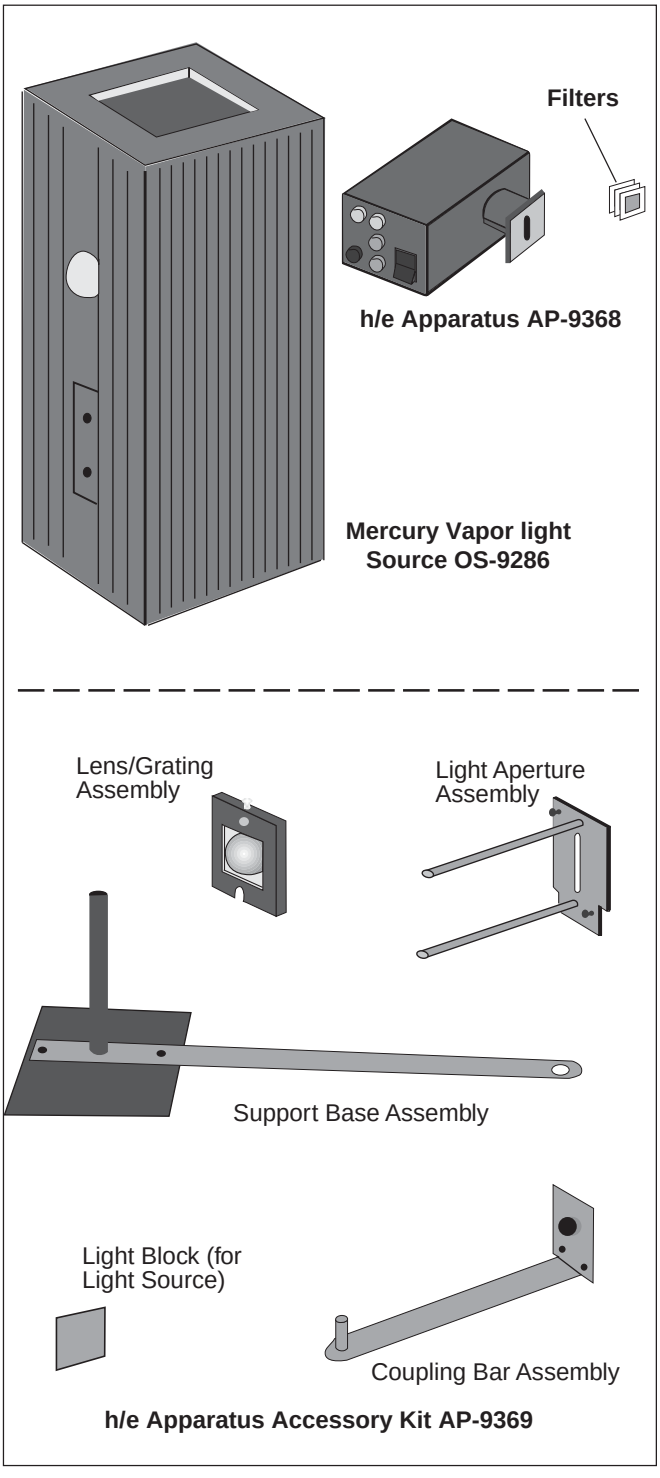


Figure 3. h/e Equipment Identification

* These items may be purchased separately from PASCO scientific, or together as an AP-9370 h/e System.

Equipment Required:

– Digital voltmeter (SE-9589)
– h/e Apparatus, (AP-9368*)
– h/e Apparatus Accessory Kit, (AP-9369*)
– Mercury Vapor Light Source, (OS- 9286*)

Installing the Batteries

The h/e Apparatus requires two 9-volt batteries (supplied but not installed). The battery compartment is accessed by loosening the thumbscrew on the rear end panel, and removing the cover plate.

➤ **NOTE:** The h/e Apparatus can also be powered using a ±9 V dual power supply. Just remove the batteries and connect +9 V to the "+6 V MIN" battery test terminal and -9 V to the "-6 V MIN" battery test terminal.

Battery Voltage Check

Although the h/e Apparatus draws only a small amount of current and batteries normally last a long time, it's a good idea to check the output voltage before each use. Battery test points are located on the side panel of the Apparatus near the ON/OFF switch. Batteries functioning below the recommended minimum operating level of 6 volts may cause erroneous results in your experiments.

To check the batteries, use a voltmeter to measure between the OUTPUT ground terminal and each BATTERY TEST terminal (-6V MIN and +6V MIN). If either battery tests below its minimum rating, it should be replaced before running experiments.

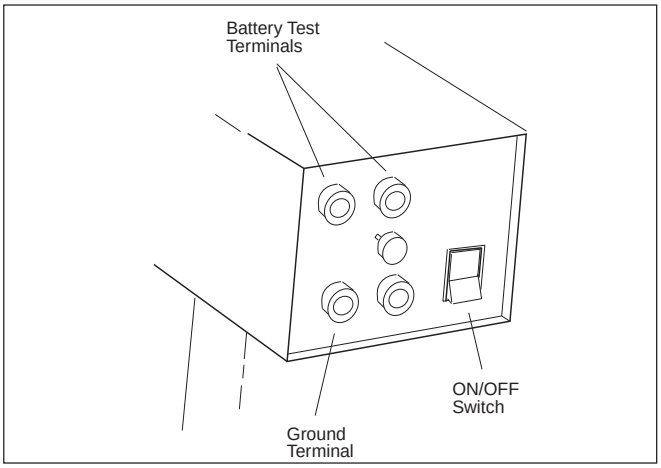


Figure 4. Battery Test Points

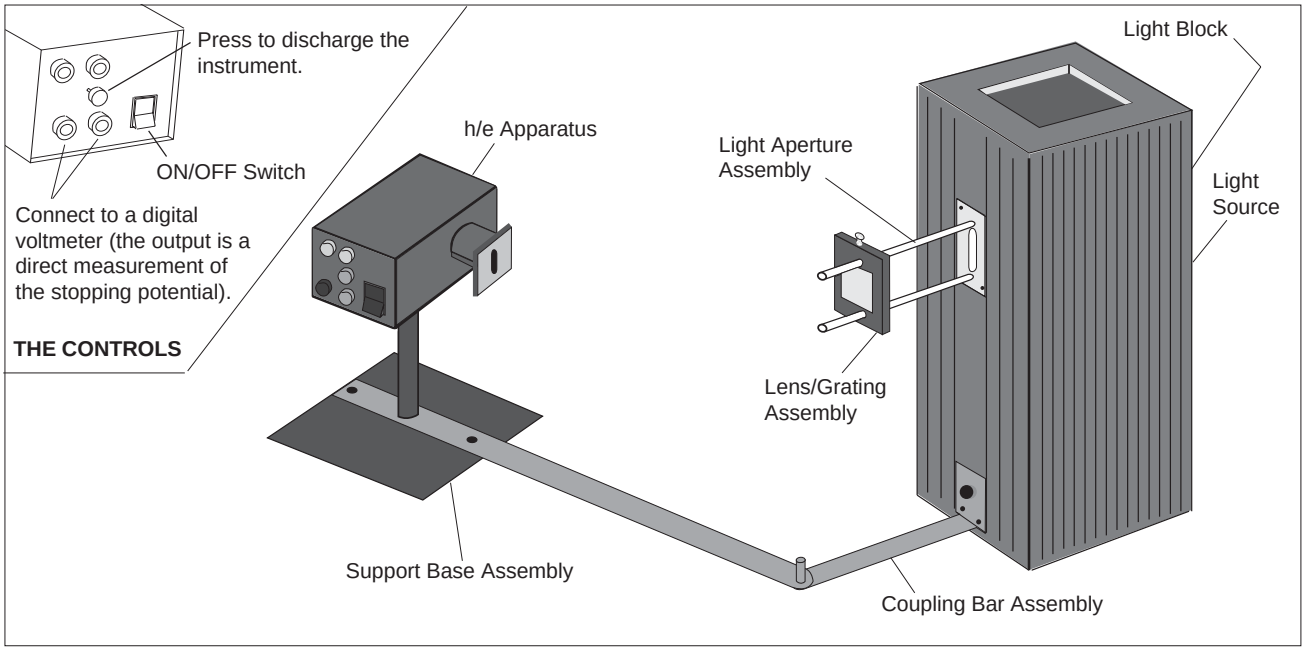


Figure 5. Equipment Setup Using a Mercury Vapor Light Source and the h/e Apparatus

Equipment Setup

The standard setup for h/e experiments is shown in Figure 5. Details for setting up the apparatus are described below.

1. The Light Source design allows simultaneous connection of two Light Aperture assemblies: one on the front and one on the back. If you are using only one Light Aperture and h/e Apparatus, install the Light Block (supplied with the Accessory Kit) in the mounting groove closest to the body of the housing on the back of the Light Source (see Figure 6).
2. Slide the Light Aperture Assembly into the center mounting groove on the front of the Light Source. Secure it in place by finger-tightening the two thumbscrews against the front of the Light Source housing.
3. The Lens/Grating Assembly mounts on the support bars of the Light Aperture Assembly (Figure 7). Loosen the thumbscrew, slip it over the bars, and finger-tighten the thumbscrew to hold it securely.

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

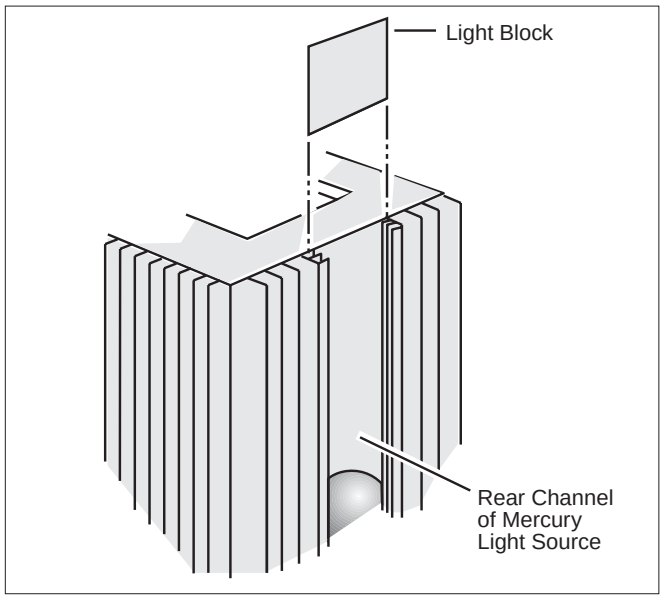


Figure 6. Installing the Light Block

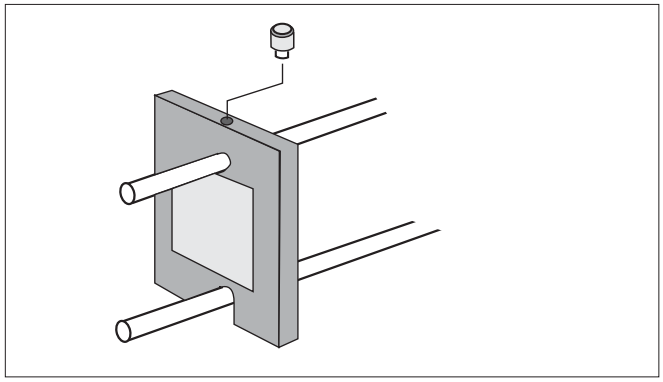


Figure 7. Lens/Grating Mounting Detail

4. Turn on the Light Source and allow it to warm up for five minutes. Check the alignment of the Light Source and the Aperture by looking at the light shining on the back of the Lens/Grating assembly. If necessary, adjust the back plate of the Light Aperture Assembly by loosening the two retaining screws (Figure 8) and sliding the aperture plate left or right until the light shines directly on the center of the Lens/Grating Assembly.

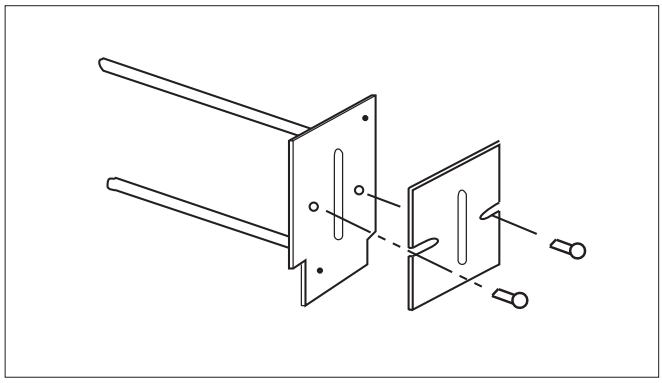


Figure 8. Light Aperture Adjustment

5. Insert the Coupling Bar assembly into the lower mounting groove of the Light Source (Figure 5). Secure in place by tightening the thumbscrew against the front of the Light Source housing.
6. Remove the screw from the end of the Support Base rod. Insert the screw through the hole in the Support Base plate and attach the rod to the Support Base plate by tightening the screw (use Phillips drive screwdriver).
7. Place the h/e Apparatus onto the Support Base Assembly.
8. Place the Support Base assembly over the pin on the end of the Coupling Bar assembly.
9. Connect a digital voltmeter (DVM) to the OUTPUT terminals of the h/e Apparatus. Select the 2V or 20V range on the meter.
10. Set the h/e Apparatus directly in front of the Mercury Vapor Light Source. By sliding the Lens/Grating assembly back and forth on its support rods, focus the light onto the white reflective mask of the h/e Apparatus (Figure 9).

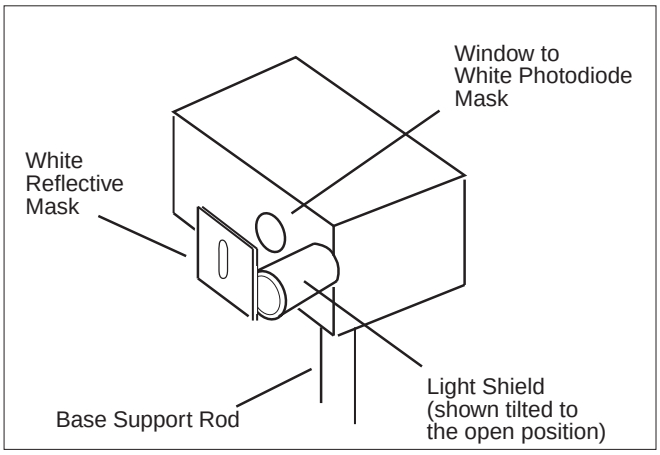
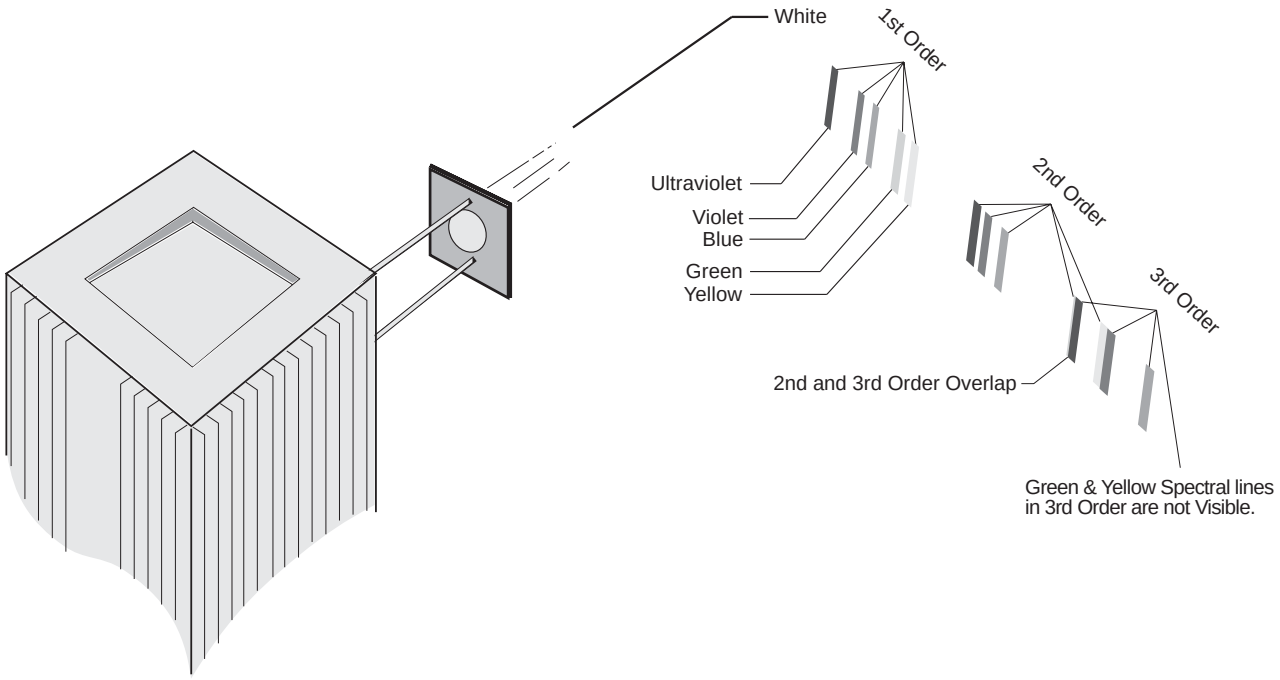


Figure 9. h/e Light Shield

11. Roll the light shield of the Apparatus out of the way to reveal the white photodiode mask inside the Apparatus. Rotate the h/e Apparatus until the image of the aperture is centered on the window in the photodiode mask. Then tighten the thumbscrew on the base support rod to hold the Apparatus in place.
12. As in step 9, slide the Lens/Grating assembly back and forth on its support rods, until you achieve the sharpest possible image of the aperture on the window in the photodiode mask. Tighten the thumbscrew on the Lens/Grating assembly and replace the light shield.
13. Turn the power switch ON. Rotate the h/e Apparatus about the pin of the Coupling Bar Assembly until one of the colored maxima in the first order shines directly on the slot in the white reflective mask. Rotate the h/e Apparatus on its support base so that the same spectral maxima that falls on the opening in the White Reflective Mask also falls on the window in the photodiode mask.

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

When making measurements it is important that only one color falls on the photodiode window. There must be no overlap from adjacent spectral maxima.



All values except wavelength for yellow line are from *Handbook of Chemistry and Physics, 46th ed*. The wavelength of the yellow was determined experimentally using a 600 line/mm grating.

NOTE: The yellow line is actually a doublet with wavelengths of 578 and 580mm.

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

Figure 10. The Three Orders of Light Gradients

14. Press the "PUSH TO ZERO" button on the side panel of the h/e Apparatus to discharge any accumulated potential in the unit's electronics. This will assure the Apparatus records only the potential of the light you are measuring. Note that the output voltage will drift with the absence of light on the photodiode.
15. Read the output voltage on your digital voltmeter. It is a direct measurement of the stopping potential for the photoelectrons. (See *Theory of Operation* in the Technical Information section of the manual for an explanation of the measurement.)

➤ **NOTE:** For some apparatus, the stopping potential will temporarily read high and then drop down to the actual stopping potential voltage.

Using the Filters

The (AP-9368) h/e Apparatus includes three filters: one Green and one Yellow, plus a Variable Transmission Filter. The filter frames have magnetic strips and mount to the outside of the White Reflective Mask of the h/e Apparatus.

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

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

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

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

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

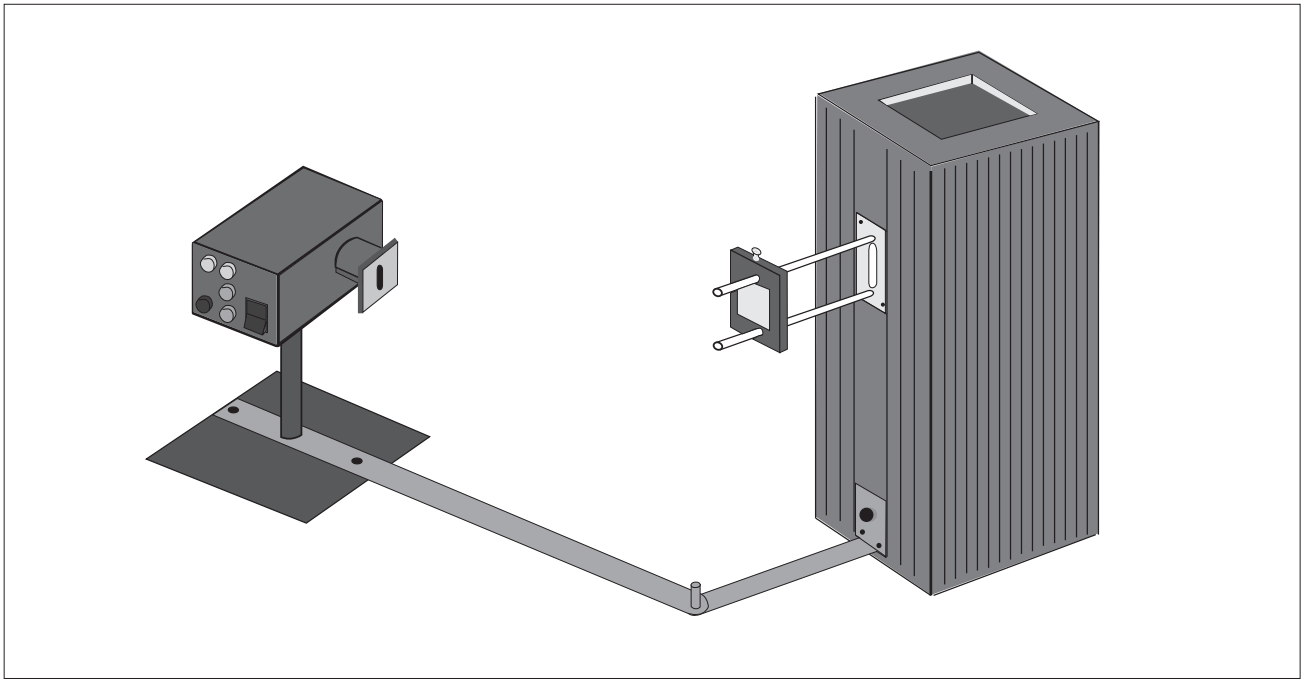
This lab investigates both of these assertions. Part A selects two spectral lines from a mercury light source and investigates the maximum energy of the photoelectrons as a function of the intensity. Part B selects different spectral lines and investigates the maximum energy of the photoelectrons as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

Setup

Set up the equipment as shown in the diagram below. 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.

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.



Experiment 1. Equipment Setup

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.

   Repeat Step 3 until you have tested all five sections of the filter.

   Repeat the procedure using a second color from the spectrum.

Color #1 _____ (name)	**%Transmission**	**Stopping Potential**	**Approx. Charge Time**
	100		
	80		
	60		
	40		
	20		
Color #2 _____ (name)	**%Transmission**	**Stopping Potential**	**Approx. Charge Time**
	100		
	80		
	60		
	40		
	20		

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 the Variable Transmission Filter has on the stopping potential and thus the maximum energy of the photoelectrons, as well as the charging time after pressing the discharge button.
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.

   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.

Light Color	Stopping Potential
Yellow	
Green	
Blue	
Violet	
Ultraviolet	

Notes

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.

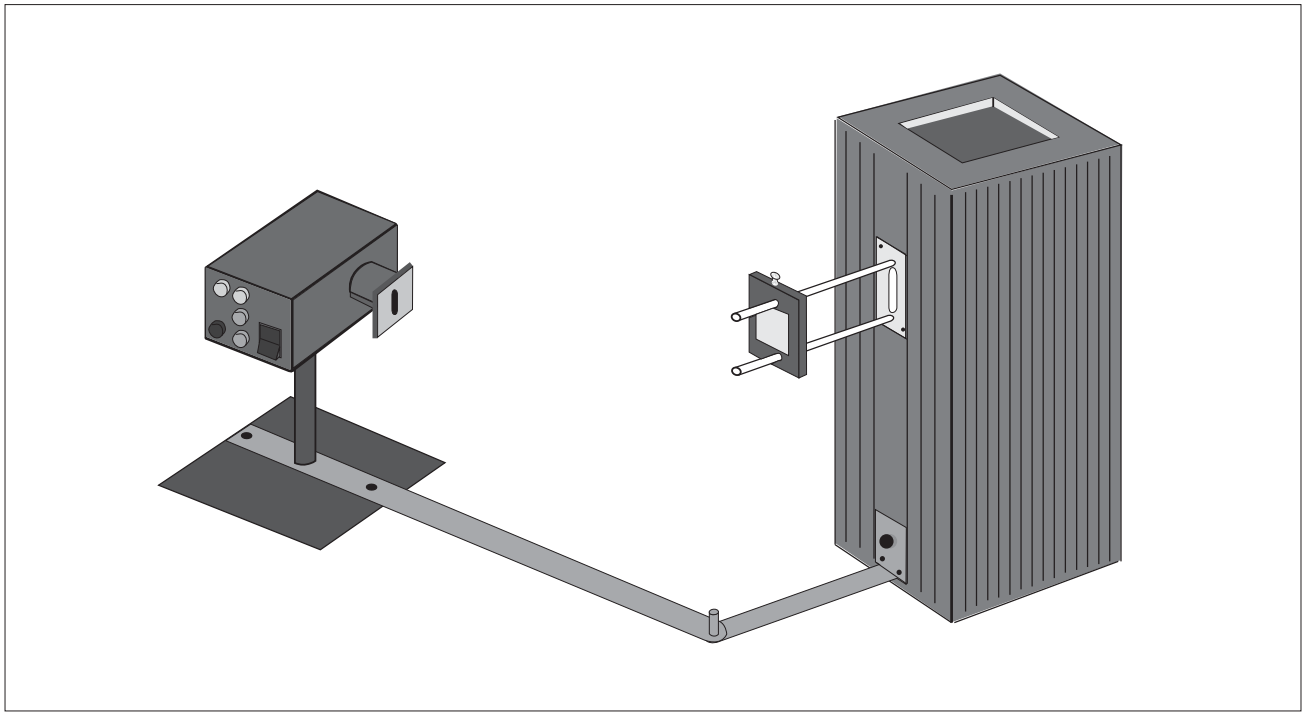
In this lab you will select different spectral lines from mercury and investigate the maximum energy of the photoelectrons as a function of the wavelength and frequency of the light.

Setup

Set up the equipment as shown in the diagram below. 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.

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. 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.



Experiment 2. Equipment Setup

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 below.

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 W_O/e ratio. Calculate *h* and W_O.

In your discussion, report your values and discuss your results with an interpretation based on a quantum model for light.

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

Technical Information

Theory of Operation

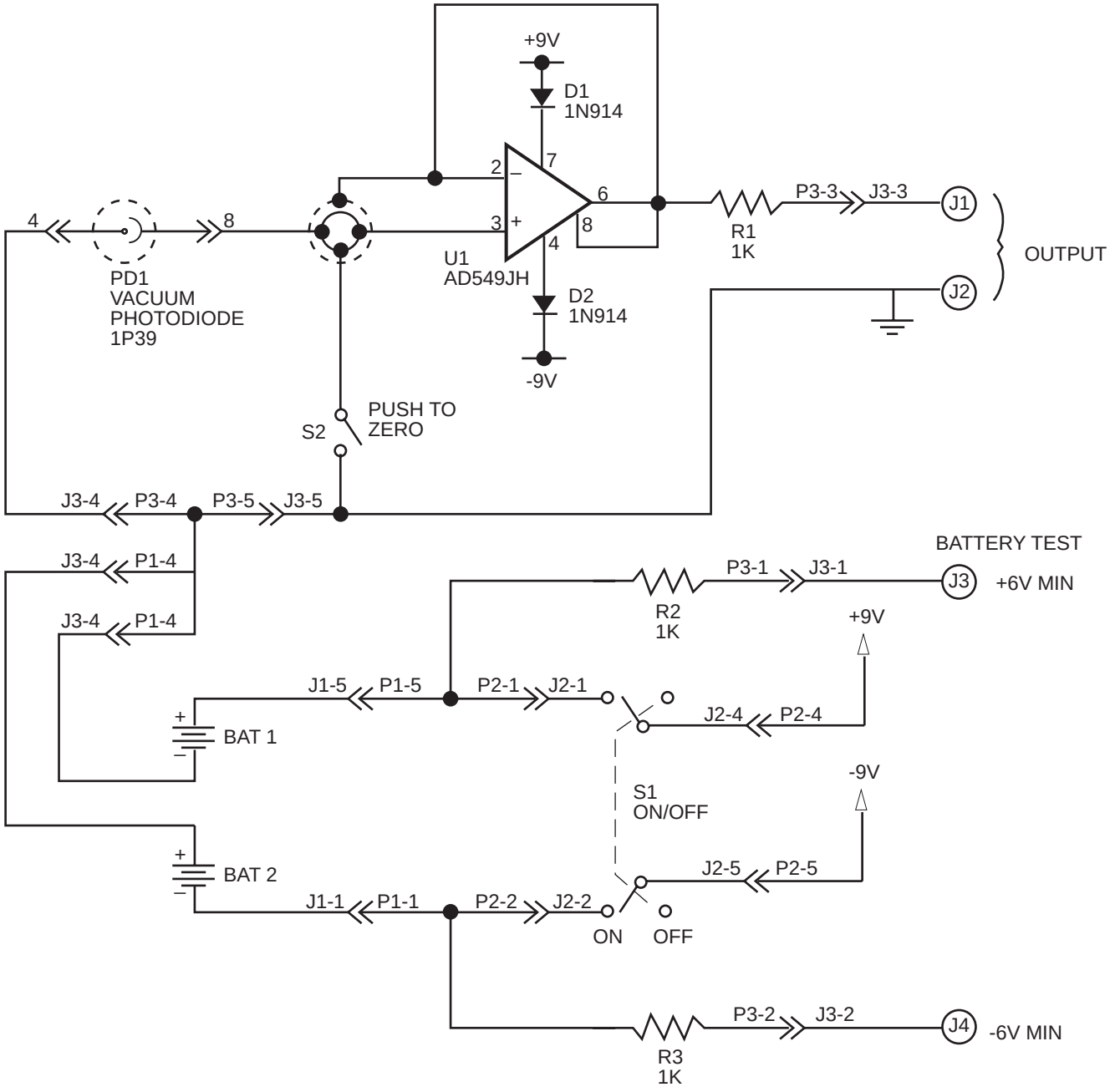
In experiments with the h/e Apparatus, monochromatic light falls on the cathode plate of a vacuum photodiode tube that has a low work function, W_0. Photoelectrons ejected from the cathode collect on the anode.

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.

To let you measure the stopping potential, the anode is connected to a built-in amplifier with an ultrahigh input impedance ($> 10^{13}$ Ω), and the output from this amplifier is connected to the output jacks on the front panel of the apparatus. This high impedance, unity gain (Vout/Vin = 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. Therefore a shorting switch labeled “PUSH TO Zero” enables the user to quickly bleed off the charge. However, the op-amp output will not stay at 0 volts after the switch is released since the op-amp input is floating.

Due to variances in the assembly process, each apparatus has a slightly different capacitance. When the zero switch is released, the internal capacitance along with the user's body capacitance coupled through the switch is enough to make the output volatge jump and/or oscillate. Once photoelectrons charge the anode the input voltage will stabilize.



Schematic Diagram