

Physics 54

Modern Physics Laboratory

Spring 2007

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Week	Section 1 Wednesday	Section 2 Thursday	Section 3 Friday
January 14th	No Meeting	Orientation	Orientation
January 21st	Orientation	1A	1A
January 28th	1A	1B	1B
February 4th	1B	2A	2A
February 11th	2A	2B	2B
February 18th	2B	3A	3A
February 25th	3A	3B	3B
March 4th	3B	4A	4A
March 11th	Spring Break	Spring Break	Spring Break
March 18th		4B	4B
March 25th	4B	5A	Cesar Chavez Day
April 1st	5A	5B	5A
April 8th	5B		5B
April 15th			
April 22nd	Tech Rpts Due	Tech Rpts Due	Tech Rpts Due

Comments:

The manual contains instructions for more experiments than you will be doing this semester.

The semester is divided into 5 two-week modules. You will do five or six experiments from the following list:

Experiments 2, 3, 7, 8 (two-week experiments);
Either Experiment 10 (two-week experiment) or Experiments 4 and 9 (one-week experiments).

As there is only one set-up for each of the experiments, you will doing them in a random order.

EXPERIMENTS

- 1 Franck-Hertz Experiment
- 2 Thermal Radiation
- 3 Rutherford Scattering
- 4 Hall Effect
- 5 Alpha Particle Absorption
- 6 Beta and Gamma Absorption
- 7 Gamma Radiation Interactions
- 8 Barrier Penetration
- 9 Photoelectric Effect
- 10 Cavendish Experiment
- 11 Speed of Light

General Instructions

In preparing for the first laboratory meeting for each experiment, you should carefully read the instructions for a scheduled experiment *before* reporting to the laboratory meeting. In many cases, you will also find it useful to do some background reading on the subject, in your Physics 52 textbook, in various sources found in the library, or on the internet. (Beware of material on the internet. Some of it is very good, but there is no guarantee that the information is relevant, useful, or correct!) You are encouraged to take notes on your reading and attach these notes in your lab book. Be sure to include references to your sources. While you may find some details of the instructions will have been changed in the lab (as we are constantly tweaking the equipment), complete familiarity with the objectives and general procedures of the experiment before the laboratory period will help you in working efficiently in lab.

Please observe the precautions emphasized in the laboratory instructions and appendices and accord the research-type equipment the respect it deserves. Note that much of the equipment in this laboratory is one-of-a-kind, delicate, difficult to repair, and expensive! Much of it can be damaged if used incorrectly. **If you have any questions about how to use the equipment, be sure to ask the instructor before turning it on or starting a new procedure.** Report any damaged equipment to your instructor immediately.

- Always bring your lab manual, a calculator, a (non-erasable) pen, and a laboratory notebook (brown-cover National 43-648 "Computation Notebook") with you to lab.

Laboratory Notebook

You will follow the same general rules for your laboratory notebook that were used in Physics 53. The following instructions are taken, with some modifications, from the Physics 53 lab manual:

The notebook will be an essential part of your laboratory work this year, and it should contain a running account of the work you do. Entries should be made while the experiment is in progress, and you should use a standard format. Your notebook should:

1. provide the reader with a table of contents at the beginning, page 1, listing the number and title of the experiment, the date or dates when it was done, the page numbers in the notebook, and the name of your partner (see below);
2. contain all pertinent information, schematic diagrams, observations, data, rough calculations, results, and conclusions. Think of your entries as being those in an informal diary or journal relating daily experiences.

In the laboratory, each experiment will be performed by a team of two investigators. Each person is responsible for the complete documentation of the work performed and its analysis. That is, while you may discuss the experimental results with your lab partner, **your analysis of the experiment should be done individually.** Remember, you will write a technical report

based on one of the experiments, and therefore a complete record of your observations and conclusions is essential.

Computers are available for data gathering, plotting, and analysis. Do not alter the computer operating system or programs in any way. Any such tampering, even if intended to be harmless, is considered a serious offense.

There are some **general rules** for making entries in your **laboratory notebook**:

1. Use permanent ink, not pencil or erasable ink.
2. Do not use scratch paper--**all** records must be made directly in the notebook. (Left-hand pages may be used for scratch work.)
3. Do not erase or use "white out"--draw a single line through an incorrect entry and write the correct value nearby. Apparent errors sometimes later prove to be important.
4. Record data in tabular form when possible with uncertainties and give units in the heading of each column.
5. Define all symbols used in diagrams, graphs, and equations.
6. Determine the uncertainties in your data and results as you go, and let the calculations determine the number of measurements needed.
7. Record qualitative observations as well as numbers and diagrams.
8. Take care in drawing **graphs**--a sloppy graph or one drawn to an inadequate scale is next to useless. Graphs often dictate what you should do next. Try to determine the probable range of your data before starting your graph. Draw graphs *in your notebook as the experiment proceeds* to help record and understand the experiment in real time. You will often find it useful to use the computer to generate graphs while you are taking data as well as when you are doing final analysis or fitting.

Append *clearly and fully labelled* computer-generated or hand-drawn graphs securely to the notebook pages. Describe these graphs in your narrative. Place the graphs in your lab books as close as possible to the relevant data, *preferably on left-hand pages facing the corresponding data tables*. Include **error bars and properly weighted fits to the data** wherever possible. Also include plots of **residuals** (with appropriate error bars) where applicable.

9. Do not fall into the habit of recording only your data in lab, leaving blank pages or spaces for description and calculation to be finished later. Entries should be made in order corresponding to the work you are doing, much like a diary report, although complicated computations and analyses are usually undertaken after the data taking procedures have been completed.

10. While not everyone can produce a showcase-type notebook, your work should be as neat and orderly as possible. Sloppiness and carelessness cannot be overlooked even when the results are good.
11. Your notebook will be a success if you *or a colleague* could use it as a guide in repeating or expanding upon the particular experiment at a much later date.

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Because your success in the laboratory will depend to a large extent upon your notebook and the write-up you produce from it, the following **specific instructions** for your notebook are provided.

A. Notebook. The physics laboratory books (National 43-648 "Computation Notebook") are bound notebooks ruled horizontally and vertically into squares. Leave two pages at the beginning of the notebook for a table of contents. Pages are numbered in the upper right-hand corner, beginning with the first page in the book. Page 1 will be your table of contents. It should contain the following column headings:

Exp. #	Title	Name and Partner	Grade	Date done	Page Nos.
Exp. 1	Sampling Theory	Sy Entist O. B. Server, partner		Oct. 3, 2006	3 - 11

- You should **date each page of your notebook**. Also **date any entry added after lab**.

B. Description of Intent and Proposed Procedure. Head each experiment with the material used in the Table of Contents. Begin with a *brief* statement of the purpose of the experiment and a brief outline of the procedure or intended procedure. Two or three sentences should be enough. There is no need to copy that contained in the laboratory manual.

Please note that you do not always have at the beginning all the information you need to prepare a full description of purpose or procedure. The objectives may be poorly defined at the start and become crystallized only in the final stages of the experiment. Your notion about how to proceed may change after you have proved something else. For these reasons we are reluctant to prescribe very definite rules about laboratory work and laboratory records

C. Sketch of Apparatus. Whenever practical, include a large, clear drawing, sketch, and/or block diagram of your experimental arrangement, to scale when necessary. Indicate clearly on the sketch critical quantities such as dimensions, volumes, masses, etc. Avoid excessive detail; include only essential features.

Record the manufacturer, model name or number, and HMC identification number and, if appropriate, the accuracy of all apparatus you use, as it may be essential that you get the SAME apparatus later, or someone else may wish to compare their results with yours.

D. Preliminary Data. Frequently there are certain preliminary data that must be measured or looked up in the tables and recorded, such as switch settings on equipment. Collect such information in a single table in your notebook and devote a separate line to each quantity. Include units and uncertainty where relevant.

E. Tabulation of Data. Put data in tabular form where practical. The easiest and most frequently used procedure is to organize the data in clear tabular form, leaving empty columns if necessary for calculated results that will be made later. This requires advanced planning. At the head of each column should appear a symbol or notation for the quantity that is to be recorded in that column, with the **units** in which this quantity is measured in parentheses, thus

$$T(^{\circ}\text{C}) \quad \text{or} \quad T(\text{K}) \quad \text{or} \quad E(\text{mV}).$$

This avoids the necessity of writing the unit after each entry. Always use one self-consistent system of units.

Uncertainties must be included for all measurements (unless you're told otherwise). If the uncertainties vary from datum to datum, each should be followed by its own uncertainty. Uncertainties should also be listed at the top of each column if possible. Thus,

$$T(^{\circ}\text{C})(\pm 0.1^{\circ}\text{C}), \quad E(\text{mv}) (\pm 0.2\text{mv}), \quad \text{wt}(\text{g}) (\pm 0.0002\text{g})$$

F. Computation and Results. After the data are recorded, there will generally be some calculations to be made. Make calculations as you go along to verify that your data is giving reasonable results; do not postpone all calculations until the final week of the experiment. If the data are all treated by some standard procedure, **describe the procedure** briefly for each calculation, giving any formulas that are to be used. (**Define** any **quantities** appearing in the formula that have not previously been defined.) Always **give a sample calculation**, starting with the formula, substituting experimental numbers, and carry the numerical work down to the result. **DO NOT SUBMIT** a computer program in lieu of a sample calculation. Your results should be compared with accepted values if possible. Information from a handbook or any reference source must be identified by book and page.

G. Summary of the Experiment. At the end of an experiment you should **type a two-page summary** containing a concise discussion of important points of the experiment, including the purpose, theoretical predictions you are testing (if appropriate), a *brief* outline of experimental methods, results, analysis, and conclusions. There is no need to put in detailed procedural discussions unless they bear directly on understanding some aspect of the data. In discussing results, you can make references (with page numbers) to specific entries – such as tables, figures, and calculations – in your lab notebook.

Be sure to refer to or include in your summary well-documented graphs of *important* findings. Discuss the major sources of random and systematic errors, including possible methods of

reducing them. If you have a hunch about the source of a discrepancy, make some order of magnitude estimates, make some approximations, and check *quantitatively* to see if hunch could reasonably explain the discrepancy. If relevant, compare your results with theoretical predictions. Your *results* should be *as quantitative and precise as possible*. Your *conclusions* should also be *as specific as possible*, given your experimental results and analysis.

This summary should be attached to the end of your lab notebook write-up; it is a significant part of the record of your experiment.

H. Honor System. All work that is handed in for credit in this course, including laboratory reports, is regulated by the Harvey Mudd Honor Code, which is described in general terms in the student handbook. In application, this Code means simply that *all work submitted for credit shall be your own*. You should not hesitate to consult texts, the instructor, or other students for general aid in the preparation of laboratory reports. However, *you must not transcribe another student's work without direct credit to him or her, and you must give proper credit for any substantial aid from outside your partnership*. Again remember that while you may discuss the experiment with your lab partner, your analysis of the experiment should be done individually.

THE FRANCK-HERTZ EXPERIMENT

This experiment was performed by Franck and Hertz in 1914, following by one year Bohr's publication of the theory of the hydrogen spectrum. The Bohr theory, utilizing Rutherford's nuclear atom, is based upon a mechanical model--an electron circling about a proton in a manner described by a new law of mechanics. The observations supporting the theory, and which necessitated a new description of atomic systems, were electromagnetic. Light is emitted and absorbed by atoms. The Bohr theory of hydrogen was a success because the energy difference between the various mechanical states of the electron-proton system corresponded, through the Einstein frequency condition $E = h\nu$, to observed frequencies of emitted and absorbed radiation. The Franck-Hertz experiment, on the other hand, was a direct mechanical confirmation of an essentially mechanical theory.

The optical spectrum of mercury vapor shows distinct emission and absorption lines corresponding to transitions between discrete energy levels of the mercury atom. Franck and Hertz found that discrete transitions of the mercury atom could also be produced by the inelastic scattering of electrons from the atom. Consider the system of an electron with some initial kinetic energy incident upon a mercury atom at rest in the ground state. If the electron energy is less than the energy required to excite the atom to its first excited state, the collision must be elastic. The kinetic energy of the electron-atom system cannot change. Due to the disparity of masses, the kinetic energy of the electron itself is essentially unchanged in the collision. If the electron energy equals or exceeds the energy for exciting the first level, however, the collision may in some cases be inelastic. The kinetic energy of the system is, in these cases, different after the collision than before. In an inelastic collision some of the initial kinetic energy is converted to potential or "excitation" energy of the atom. In due course, this energy is radiated from the excited atoms as light, but the primary interaction is one described in mechanical terms. Franck and Hertz observed such inelastic collisions by monitoring the current of electrons passing through a mercury vapor.

Apparatus

The apparatus consists of a special electron tube containing a small quantity of mercury. The vapor pressure of mercury in the tube is adjusted by placing the tube in a furnace whose temperature may be varied. Electrons emitted from the cathode must, then, traverse a controlled mercury atmosphere in reaching the anode of the tube (see Fig. 1).

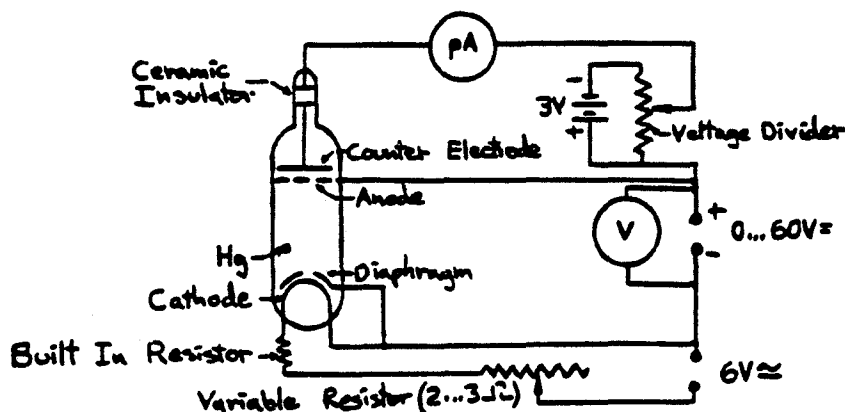


Fig. 1. Franck-Hertz Electron Tube and Circuit.

The anode is perforated so that many of the electrons will pass through it and collect on the counter-electrode.

Emission current from the cathode is controlled by the temperature of the cathode and by the potential applied to the anode. A diaphragm connected to the cathode limits the current and eliminates secondary and reflected electrons, making the electric field more uniform.

Electrons which pass through the hole in the diaphragm are accelerated through the mercury atmosphere by the positive potential applied to the anode. The counter-electrode is maintained at a potential of approximately -1.5 V with respect to the anode. Thus no electrons which pass through the perforated anode with energy less than 1.5 eV can reach the counter-electrode.

If the electrode and the cathode were of the same material and if all electrons were released from the cathode with zero kinetic energy, then the current of electrons collected by the counter-electrode would vary with the anode potential in the following way. No current would be observed until the potential of the anode exceeded 1.5 V. As the potential increased, all electrons passing through the anode would reach the counter-electrode and the current would show a continuous increase with rising potential until a potential corresponding to the energy transition from the ground to the first excited state of mercury is reached. At this point the current would drop abruptly with increasing potential, since many electrons would make inelastic collisions with mercury atoms and have insufficient kinetic energy to reach the counter-electrode. If the potential were sufficiently increased, however, the electrons would again reach the counter-electrode even after making an inelastic collision. This second increase in current would continue until the electrons gained enough energy to make two inelastic collisions, again not being left with enough kinetic energy to reach the counter-electrode. This would result in a second sharp drop in current. If the above conditions were satisfied, a succession of current maxima with sharp breaks would be observed with increasing potential.

The fact that the counter-electrode and the cathode may not be of the same material makes the first maximum an unreliable measure of the excitation potential of mercury. A so-called "contact" potential must be added to or subtracted from the observed potential. Evaluation of the contact potential is avoided by measuring potential differences between succeeding maxima. The fact that electrons are not emitted from the cathode with zero kinetic energy means that the actual energy distribution is superimposed upon that established by the anode potential. Sharp breaks are thus washed out of the current-voltage curve.

Electrical Circuit

The circuit employed in this experiment is shown in Fig. 1. All voltage sources indicated in the figure are located in a power supply which is connected to the furnace by means of various power cables. The measuring amplifier is a separate unit, but the microammeter which reads the counter-electrode current is mounted in the front of the power supply. A voltmeter (0 - 50 V) on the front of the power supply reads the anode potential, and a third small voltmeter is used for the bias voltage and the voltage across the filament.

Filament current is supplied by a 6.3 V transformer and bridge rectifier. The anode and bias potentials are derived from dry cells mounted inside the power supply. All potentials are controlled by knobs on the front of the power supply. There are also two switches on the front of the power supply, the "POWER" switch and the "ANODE" switch. Filament potential alone is supplied with only the POWER switch on. The ANODE switch must be on for both anode and bias potentials.

Procedure

The oven in which the tube is mounted should be turned on immediately upon entering the laboratory. The temperature inside the oven is controlled by an external regulator. A thermometer protruding from the top of the cabinet provides a measurement of the temperature near the mercury tube. Close attention should be given to the reading of the thermometer so that a temperature of 180°C is at no time exceeded. By means of the thermostat control knob, the temperature of the oven should be adjusted initially to $170^{\circ}\text{C} \pm 5^{\circ}\text{C}$. Check the oven temperature every few minutes.

The Leybold measuring amplifier should also be turned on immediately so that it will have ample time to stabilize. As the temperature of the tube approaches its operating value, the power supply POWER switch should be turned on.

Set the sensitivity range of the measuring amplifier at 30×10^{-10} , turn the sensitivity control knob to its central position, and zero the microammeter by means of the "zero" control knob on the amplifier. The input signal to the amplifier may be grounded at the time these settings are made, but the grounding connection on the front of the amplifier must be turned off, 0, before any current measurements can be made.

When the operating temperature is reached, first make sure that the ANODE voltage control knob is turned to the full counterclockwise (zero) position; then turn the ANODE switch on.

Increase the filament voltage to the value suggested at your station. Slowly increase the anode potential to about 35 v. Watch the microammeter carefully. If the current increases suddenly, an electrical breakdown has occurred in the tube, and the potential must be reduced to zero immediately. If such a breakdown has occurred, reduce the filament voltage very slightly and again try to raise the anode potential to 35 v. (If the tube still breaks down, see your instructor.) Now very slowly increase the anode potential to 40 v and adjust the sensitivity knob to give a full scale deflection of the microammeter for the maximum current observed in the 30-40 v range. Allow time for the current to stabilize after each small adjustment and watch out for the onset of electrical breakdown.

The apparatus is now ready for taking measurements. Slowly decrease the anode potential and observe the microammeter deflection. Dips and peaks in the current should be obvious in the 0-40 v range. The sensitivity range of the amplifier may have to be changed in order to define the maxima clearly at the lower anode voltages. Record counter-electrode currents vs. anode potential. Note that small temperature changes will affect the current at a given voltage (why?), so monitor the oven temperature as you make your measurements. Plot your data and determine the excitation energy of mercury.

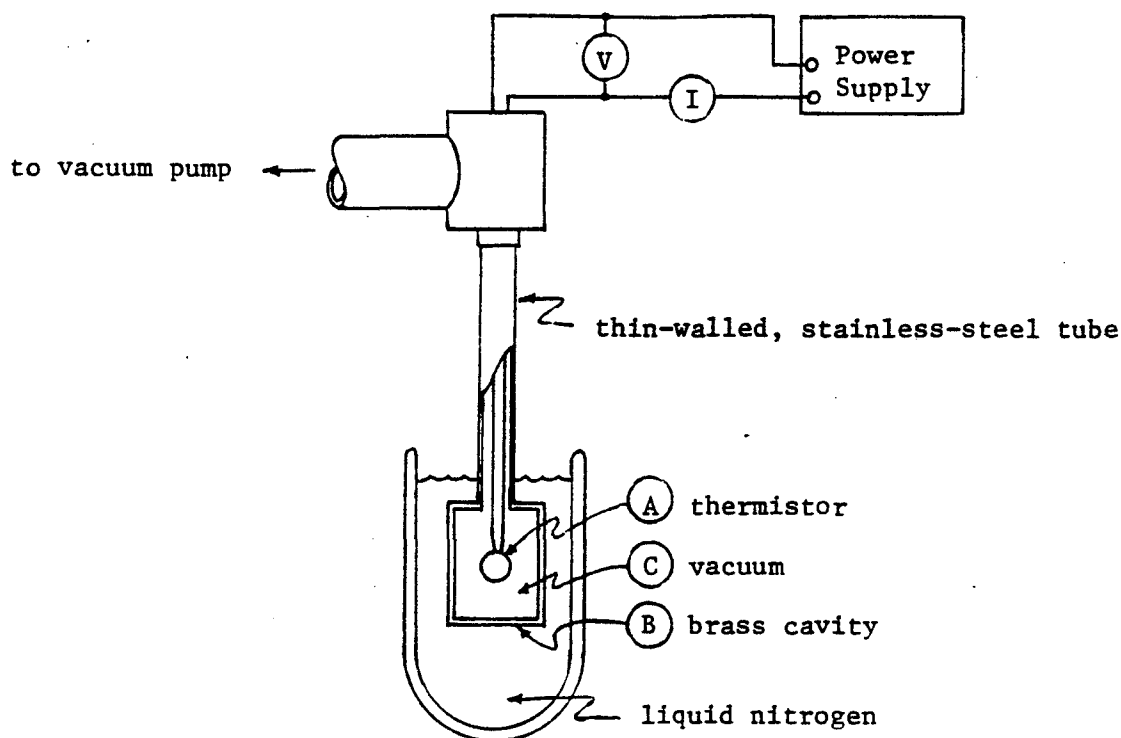
Repeat your measurements while slowly increasing the anode voltage from 0 to 40 v. Repeat with different oven temperatures. (Do not exceed 180°C .) For each temperature you should reset the sensitivity knob following the original procedure.

From all your data obtain your best estimate of the excitation energy of mercury.

THERMAL RADIATION

General

Apparatus for study of the propagation of thermal energy by radiation is shown schematically below:



Any surface at a temperature above absolute zero radiates energy in the form of electromagnetic radiation. When the surface is in a vacuum, as in this case, radiation is the only mechanism for energy loss. One imagines that the surface of [A] is at some temperature T and asks at what rate W thermal energy is radiated from the surface. Since [C] is a vacuum, the rate can depend only upon the nature of the surface and its temperature. The surface has been blackened in this experiment to eliminate any effect due to the nature of the surface other than its area A . The rate of energy loss may be expressed as

$$P = \sigma AT^x \quad (1)$$

The universal constant σ is called the Stefan-Boltzmann constant. We are to determine σ and the exponent " x " relating W to the surface temperature.

The interior surface of the brass cavity [B] also radiates thermal energy to [A]. This surface, however, is maintained at a sufficiently low temperature (77°K) by contact with liquid nitrogen that the energy received by [A] from [B] is negligible. Further, [A] is suspended by wires of very small cross-section to reduce conduction of energy to [A] from the room. In equilibrium, then, the rate at which energy is radiated through the vacuum from [A] must equal the rate at which it is generated electrically within [A].

The radiating element [A] in this experiment is a thermistor. Thermal energy (in watts) is generated within it at a rate given by

$$P = VI \quad (2)$$

where V (in volts) and I (in amperes) are measured by the meters "V" and "I" shown.

The resistance R of a thermistor varies as a function of its temperature. Since

$$R = V/I \quad (3)$$

measurement of V and I determines not only P but R as well.

Thermistor calibration

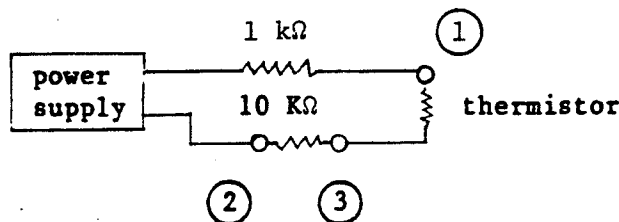
The conductivity of a thermistor (semiconductor) is proportional to the Boltzmann factor $\exp(-E/kT)$ where T is the temperature ($^{\circ}\text{K}$), k the Boltzmann constant ($8.616 \times 10^{-5} \text{ eV K}^{-1}$) and E the "band-gap" energy of the semiconductor--the energy which must be acquired by an electron for it to participate in electrical conduction. The resistivity is the reciprocal of the conductivity so that the thermistor resistance may be expressed as

$$R = ae^{b/T} \quad (b = E/k) \quad (1)$$

The two constants, a and b , are determined by measurement of R at two different temperatures. Thus, if R_1 and R_2 are the resistances of the thermistor at temperatures T_1 and T_2 , then

$$\ln(R_1/R_2) = b(1/T_1 - 1/T_2) \quad a = R_1 e^{-b/T_1} = R_2 e^{-b/T_2} \quad (2)$$

Calibration is performed with atmospheric pressure in the apparatus to hasten equilibrium. First measure R at room temperature as indicated by a thermometer. The following circuit is used with a large ($10 \text{ K}\Omega$) series decade resistor to limit the power dissipation in the thermistor to the order of microwatts:



The leads of one voltmeter are connected to points [1] and [3] to give the potential across the thermistor. The second voltmeter reads the voltage drop across the decade resistor (points [2] and [3]), from which you can determine the current in the thermistor.¹ Use the

¹The $1 \text{ K}\Omega$ resistor between the power supply and the thermistor is included to protect the thermistor from damage when the decade resistance is changed.

potential and current to determine R_1 at room temperature. Then surround the thermistor bath to obtain R_2 at $T_2 \approx 273$ K. (Record the potential across the $10\text{ K}\Omega$ resistor at one- or two-minute intervals to determine when equilibrium at ice temperature is reached.) Determine a and b (and E) from these data and equations (2). Equation (1) is then used to determine T in the experiment as written.

As soon as these data are obtained, have the instructor start the mechanical and oil diffusion vacuum pumps. Approximately 30 minutes are required to reach the operating pressure of a few times 10^{-5} Torr. Use this time to analyze your calibration measurements and determine the constants a and b .

Experimental procedure

The same circuit used to calibrate the thermistor is used to measure V and I (and thus R and P) in the remainder of the experiment except that the series resistor is reduced from $10\text{ K}\Omega$ to $1\text{ K}\Omega$.

When a sufficient vacuum is obtained, establish a current of $\sim 10\text{ mA}$ just before immersing the brass cavity in liquid nitrogen. (If power is not applied to the thermistor before cooling, it will rapidly cool after immersion to a resistance so high that sufficient power cannot be applied to control its temperature.) Slowly raise the dewar of liquid nitrogen to cover the brass cavity. The current through the thermistor will drop a bit as its resistance increases. Wait several minutes for the temperature of the thermistor to stabilize. Record several voltage readings during this equilibration period to document the approach to equilibrium. Determine the thermistor temperature and the power radiated by the thermistor at equilibrium.

Vary the current slightly and again wait for equilibrium. Calculate T and P . Proceed in this way to generate data for P vs T over a temperature range of approximately 0°C to $50\text{--}60^\circ\text{C}$.

The exponent " x " is most easily found by using a log-log plot of equation (1):

$$\log P = \log (\sigma A) + x \log T \quad (4)$$

The slope of the plot $\log P$ vs $\log T$ yields the exponent in the "Stefan-Boltzmann radiation law." Determine this law from your data and evaluate the Stefan-Boltzmann constant σ , given $A = 0.52\text{ cm}^2$. Think carefully about the best way to get a value for σ .

RUTHERFORD SCATTERING

By 1911 general agreement existed that atoms contain a small number of electrons with most of the atomic mass associated with positive charge. The problem was to determine how the positive charge and mass are distributed. Two extreme views were proposed by J. J. Thomson and Ernest Rutherford. Thomson considered the atom to be made of a space filling sphere of positive charge in which the electrons were embedded--the "plum pudding" model. Rutherford considered the positive charge and mass to be contained within a central, very dense nucleus--the "nuclear atom" model.

The test of these views was suggested by Rutherford and carried out by H. Geiger and E. Marsden in 1913. The experiment is the prototype for a great many contemporary "particle experiments" of the so-called "scattering" type. The recent experiments by Hofstadter, et al., on the special distribution of charge within the nucleus itself are of this type. The experimental procedure is to send known particles (known mass, charge, etc.) with a given momentum into a thin target of the material under investigation and to observe the scattering (the change of momentum) of the emergent beam. Given any model of the target such that the forces arising between the particle and the target are known, the expected scattering can be calculated. The observed scattering then serves to eliminate those models for which the predictions disagree with experiment. Rutherford's particles were alpha particles of relatively low energy arising in natural radioactive decay. Since only electromagnetic forces are significant in this case, the experiments served to eliminate models of the positive charge distribution in an atom. The plum pudding model was definitely crossed off. The nuclear atom model, on the other hand, predicted results in very good agreement with the data.

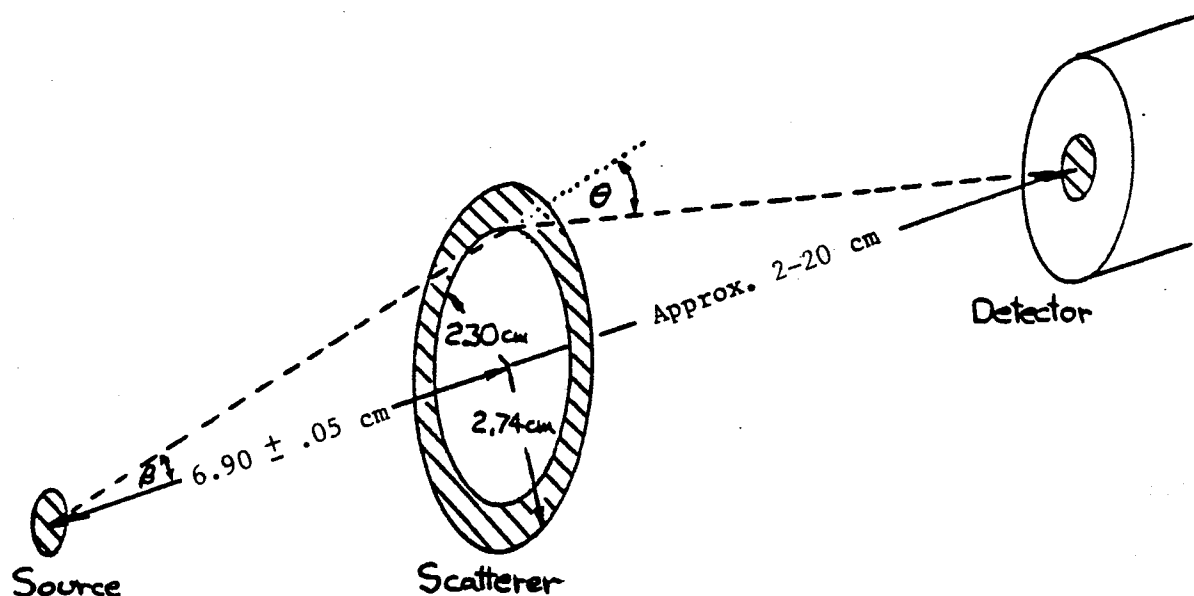
1. The Rutherford model with which the results of this experiment are compared is that of a positive charge distribution which is represented as a point charge of magnitude Ze , where Z is the atomic number of the target material. The mass distribution was considered to be the same as that of the charge or, at any rate, the center of mass was assumed rigidly attached to the point charge. The predicted angular distribution of particles of mass m and charge $Z'e$ scattered from an incident beam of particles with velocity v by atoms of atomic number Z and mass M initially at rest is

$$\sigma(\theta) = \left(\frac{ZZ'e^2}{8\pi\epsilon_0\mu v_0^2} \right)^2 \frac{1}{\sin^4(\theta/2)}$$

$$\mu = \frac{mM}{m + M}$$

The "cross section," $\sigma(\theta)$, is a measure of the probability that an incident particle will be scattered in a single collision into the angle θ to $\theta + d\theta$ measured with respect to the direction of the initial velocity.

A sketch of the relation of the source, scatterer and detector of the alpha particles in the laboratory apparatus is shown below:



The apparatus may be disassembled at the flanged end by removing the four knurled nuts. First, however, read the following description. The source and scatterer are mounted together in a movable cage such that the angle β is fixed. The source is radioactive Americium 241, which decays primarily by emitting a 5.29 MEV alpha particle.¹ The scatterer is an annulus of gold foil about 2 μm thick. Neither the Americium source nor the gold foil may be touched, for obvious reasons.

The detector is a solid-state device consisting of a silicon wafer with a thin (.02 μm), gold surface covering on one side and an aluminum surface on the other side. A potential difference of 30 v is placed across this "sandwich." When an ionizing particle passes through the silicon, electrons are ejected by collision with the particle from the filled band to the empty conduction band of the silicon semiconductor. Both the electrons and the "holes" left in the conduction band move under the applied field: the electron to the gold surface, the "holes" to the aluminum. Hence a pulse of charge is collected, the size proportional to the number of electrons ejected into the conduction band, and thus to the energy loss of the ionizing particle in the silicon. It is this pulse of charge, amplified, which you will count with a scaler. Further details are given in the appendix to this experiment.

Caution: Do not touch the detector! The gold coating is fragile, the silicon can be ruined by contamination, and static electricity could damage the detector irreversibly.

The distance from the scattering foil to the detector may be varied from about 1 to 20 cm by means of the vacuum sealed plunger attached to the source cage and extending outside the apparatus. The scattering angle θ may thus be varied from about 27 to 90 degrees.

Since the range of the alpha particles in air at normal pressure is only a few cm, it is necessary to evacuate the entire apparatus. The brass vacuum chamber is closed at one

¹ A thin cover over the radioactive source reduces the energy of the alpha particle somewhat.

Appendix:

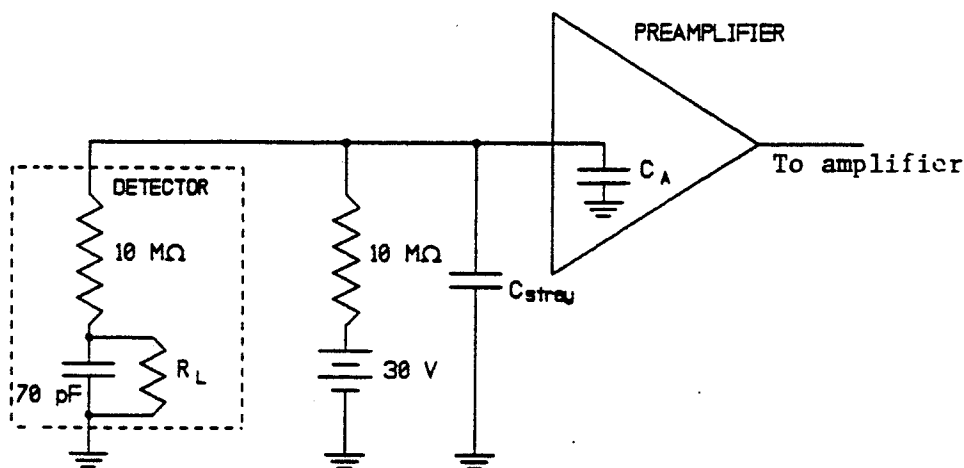
The EGG Ortec Silicon Charged Particle Detector

Silicon is a semiconductor with a gap of 1.1 electron volts between the top of the valence band and the bottom of the (nearly empty) conduction band. At any temperature above absolute zero, some electrons will have enough thermal energy to reach the conduction band; for the detector you use, with 30 volts potential difference across the silicon wafer, this gives rise to a "dark current" of about 3×10^{-7} amperes or 1×10^{12} electrons/second. (Incidentally, since the silicon wafer is about 150 μm thick, the electric field is $30\text{V}/1.5 \times 10^{-4}\text{ m} = 200,000$ volts/meter.)

When there is no voltage across the silicon wafer, the Fermi energies (see Eisenberg and Resnick, Chapter 13, pp. 507 *et seq.*) of the electrons in the gold, aluminum, and silicon are equal; electrons move between these layers to change the potential of these layers until this equality is reached. The particular silicon wafer we use has donor impurities (see E and R, p. 507), so the Fermi energy in the silicon lies 0.16 electron volts below the bottom of the conduction band. There are, accordingly, thermally ejected electrons in the conduction band. Once the 30 v power supply is turned on, these electrons are swept away, giving rise to the "dark current."

When an α particle enters the silicon, it collides with electrons in the silicon lattice, giving many of them enough energy to reach the conduction band. The average energy loss by the α -particle to create an electron-hole pair is measured to be 3.6 eV. Thus a 5 MeV α -particle, completely stopped in the silicon, gives rise to $5 \times 10^6 / 3.6 = 1.4 \times 10^6$ electron-hole pairs, or 2.2×10^{-13} coulombs. The capacitance of the detector is 70 picofarads ($7 \times 10^{-11}\text{ f}$), so collecting this charge causes a voltage change $\Delta V = 2 \times 10^{-13}\text{ coulomb} / 7 \times 10^{-11}\text{ f} = 3$ millivolts. The detector voltage is supplied through a 20 megohm resistor, so the recovery time is $RC = 7 \times 10^{-4}\text{ f} \cdot 20^7\Omega = 1.4 \times 10^{-3}\text{ sec}$.

Here is a circuit diagram of the detector, its power supply, and the first (preamplifier) stage of amplification:



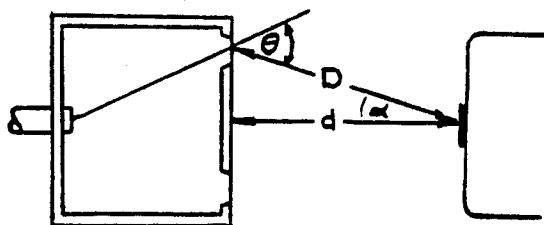
Here R_L is the "equivalent resistance" of the silicon wafer; since the "dark current" is about 3×10^{-7} amperes for a potential of 30 volts, $R_L = 100\text{ M}\Omega$. The Model 109A preamplifier set at $10 \times$ gain gives a pulse of 150 mV/MeV for a Si detector. This preamp also reduces the pulse width to approximately 50 μs . The amplifier following the preamp further reduces the pulse width as well as increases the peak voltage.

end by the sliding plunger and flange. The other end is closed by the mounting bracket of the detector seated against an O-ring seal.

Current pulses from the silicon detector generate voltage pulses in the amplifier circuit. These pulses are counted by a scaler. The experiment consists in determining the number of counts registered by the scaler in a measured time interval as the source cage plunger is moved in or out to vary the scattering angle θ .

2. Carefully study the apparatus prior to its evacuation. You will be given the minimum value of d (i.e., when the plunger is in as far as possible) for your apparatus. You will need this value together with your measurements of the external position of the plunger to compute the scattering angle θ and to correct for changes in the detector solid angle (see below).

Begin collection of data with the plunger withdrawn as far as possible to measure the counting rate for the smallest scattering angle. Record the time necessary to accumulate at least 100 counts at all scattering angles.² The standard deviation for N counts is $\sqrt{N}$ so that 10% statistics are obtained with 100 counts. The counting rate at minimum scattering angle will probably be of the order of 30 counts per minute, falling to some 4 counts per minute at the largest angles.



The counting rate must be corrected for the change in the solid angle subtended by the detector at the gold annulus. The apparent size of the detector as seen from the annulus is a function of their separation, d . Ignoring the finite size of the detector and the annulus width, this correction consists of two factors. First, the detector size would vary as $1/d^2$ were it viewed "head on" from the annulus. This is very nearly the case when d is much greater than the radius of the annulus. For

small separations, however, the projection of the detector into the line of sight from the annulus must be taken into account. The projected area goes as $\cos \alpha$, or as d/D . Combining these two factors, the apparatus size of the detector varies as

$$(d/D)(1/D^2).$$

The counting rate is multiplied by the reciprocal of this factor to obtain a counting rate proportional to that which would have been measured with a detector whose size appeared always the same to the scattering annulus. The counting rate corrected for solid angle is proportional to the cross section $\sigma(\theta)$.

To compare your results with the predictions of the Rutherford model, plot the logarithm of the corrected counting rate vs. the logarithm of $\sin(\theta/2)$. (What should this plot look like according to the Rutherford model?) Enter your data in this plot with bars to indicate the standard deviations resulting from counting statistics.

²In taking data, choose intermediate plunger positions in light of the plot you will be making. (See below)

Addendum to Experiment 3

Since the laboratory notes were written, the brass cylinder has been replaced by a plastic ("Lexan") cylinder, which is semitransparent and slightly shorter. Accordingly, the angle of scattering of the alpha particles must be calculated with the new dimensions.

The dimension you need to know is d on Page 3-3 of the notes. d is the distance from the plane of the gold scattering foil to the surface of the detector. It is also the distance between the two knurled knobs, one the handle on the plunger and the other the one the rod slides through, less .08 cm. We have placed a sleeve of length 2.00 cm on the plunger rod (to keep a bump on the can carrying the americium source and the foil from striking the detector), and therefore the shortest d available to you is 1.92 cm.

Why the Lexan cylinder, and these changes?

For reasons I did not understand, Experiment 3 usually produced an exponent in the range of -4.3 to -4.5 instead of the -4 which Professor Rutherford had in mind. Mark Chalice, '94, asked me two years ago if any of the alpha particles which go through the foil undeflected might then strike the brass cylinder wall and be scattered there. Indeed, most of the alpha particles that strike the foil do go through essentially undeflected, having lost some energy by many collisions with electrons, thus ionizing gold atoms. These alpha particles enter the brass. Most spend out their range losing energy in more electron collisions, but a few of them may indeed be scattered by the copper and zinc nuclei of atoms which make up brass. From the cross-section equation on Page 3-1 of the notes, we see that the scattering cross section depends on Z^2 . For gold, $Z = 79$; for copper, $Z = 29$, and for zinc, $Z = 30$. Accordingly, these brass nuclei are only about 14% as effective as gold in Rutherford scattering, but the path length in the brass can be considerable. From the same equation on Page 3-1, we also learn that as the alpha particle slows down, the probability of scattering increases. Thus the cylinder walls in front of the gold foil may constitute a significant second scatterer. The angle of scattering at which the alpha particle is detected is greater for these brass-scattered alphas, and hence they are no longer much detected as the foil nears the detector. Accordingly, we are led to believe that the power law is greater than 4.

The solution to the problem is not to use brass, but a plastic, for which the atoms in the wall are predominately carbon, hydrogen and oxygen. These have at most 1% of the scattering cross section of gold. Essentially all the alpha particles striking the wall lose their kinetic energy through electron collisions and are not scattered.

j.b.platt, january 1994

THE HALL EFFECT

In this experiment you will study the Hall effect in a semiconductor. Measurements of the Hall potential will yield the sign and density of the charge carriers in the semiconductor.

In preparation for this experiment you should review Halliday & Resnick, Section 33-5 (Hall Effect) and the discussion in Section 37-6 (Ferromagnetism) on the magnetization curve and hysteresis. Also see the discussion of the Hall effect in e.g. Eisberg and Resnick, Quantum Physics and Modern Physics by Robert Sproull. In connection with the following theoretical discussion you should determine the sign of the Hall potential $(V_a - V_b) = \Delta V$ in Fig. 1 for positive and negative charge carriers. Also show how the Hall potential depends on B , I , n , w and d as defined below.

Theoretical Background

The charge carriers in the conduction of electricity by metals are electrons. If a metal strip is placed in a magnetic field and a current is established in the strip, then a small transverse electric field is set up across the strip. The resulting difference of potential is the Hall potential. Note that this potential is perpendicular to both the current flow and the magnetic field (see Fig. 1.) When semiconducting materials are used in place of the metal, the Hall potential is generally much larger and may be of opposite sign. The change in sign implies that, in such cases, the charge carriers are positive and that a different conduction process is occurring than in the metals.

Two quantities are of interest here. First, the sign of the Hall potential, which depends on the sign of the charge carriers. Second, the magnitude of the potential, from which may be deduced the density of charge carriers. This deduction is briefly the following: Let E_H be the transverse electric field generated in the strip carrying a current of density j in a field B in the geometry shown above. The quantity

$$R = \frac{E_H}{jB}$$

is called the Hall coefficient. In equilibrium, the transverse force of qE_H acting on the charge carriers of charge magnitude q must just compensate the Lorentz force of qvB acting upon these charges moving with drift velocity v . Since also $j = qnv$, where n is the density of charge carriers, we have

$$R = \frac{E_H}{jB} = \frac{vB}{qnvB} = \frac{1}{qn}.$$

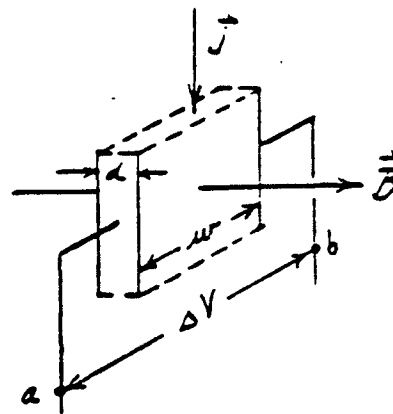


Fig. 1. The Hall Effect

For both metals and semiconductors, it turns out that $|q| = e$, the magnitude of the charge of an electron. Thus n may be calculated from measured values of R .

For a strip of width w and thickness d , carrying a uniform current density j , the conduction current is $I = jwd$.

The Hall potential is $\Delta V = E_H w$.

Thus,
$$R = \frac{\Delta V}{w} \frac{wd}{I} \cdot \frac{1}{B} = \frac{\Delta V}{IB} \cdot d$$

Measurement of the Hall Potential

1. Circuits. Figs. 2a and 2b show the circuits used in obtaining the Hall potential. Fig. 2a shows the circuit used to produce the required magnetic field and Fig. 2b shows the Hall effect circuit itself.

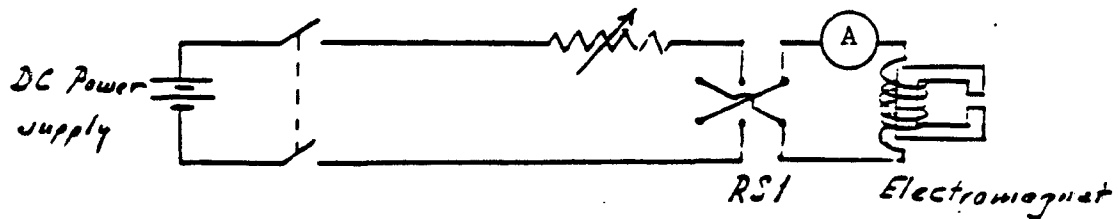


Fig. 2a. Electromagnet circuit

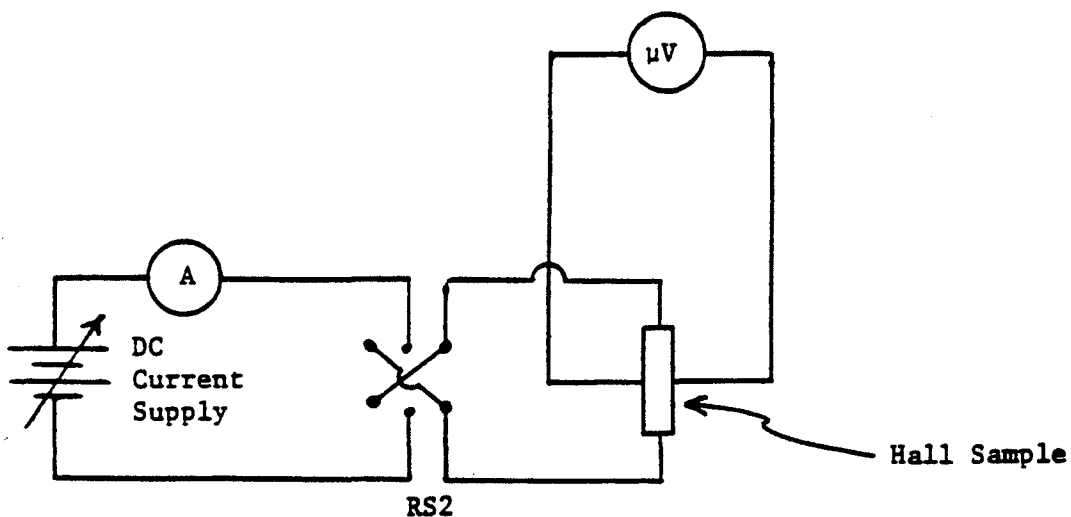


Fig. 2b

Concerning these figures, note:

The Hall effect requires both a current I passing through the sample and a magnetic field. The magnetic field is not shown in Fig. 2b, but the sample is oriented in the magnet to give the geometry shown in Fig. 1.

Two reversing switches (RS1 and RS2) are present in the circuits, one to reverse the current in the magnet, the other to reverse the direction of current flow I in the Hall effect device. The reason for RS2 is to compensate for thermal emf's which can lead to small zero offsets.

The reversing switch RS1 is included for a rather subtle reason: In an ideal Hall effect device $\Delta V = 0$ if there is no magnetic field. But you will find that $\Delta V \neq 0$ even when $B = 0$. This occurs because the sample has a finite resistance and therefore a voltage drop occurs along the direction of current flow; the potential leads are soldered onto the sample at points which are not quite on the same equipotential line (in zero magnetic field). This voltage difference between the two leads, which we'll call the IR effect, adds onto the Hall potential ΔV . In order to eliminate the IR effect, the magnetic field direction is reversed by using RS1. This changes the sign of ΔV , but since I is still flowing in the same direction, the IR effect will not change sign. The results for both magnetic field directions are averaged to get ΔV .

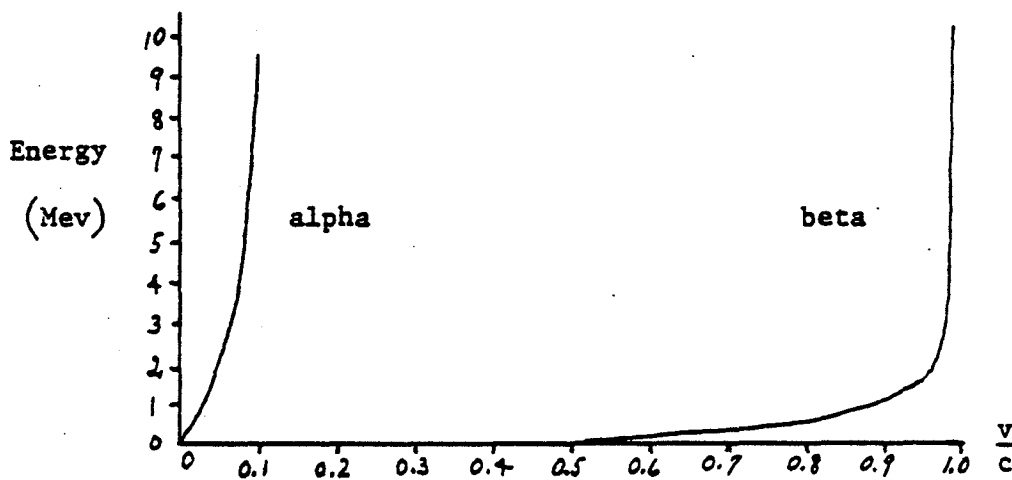
2. The Electromagnet. Calibration data for the magnet will be supplied. These data were taken along the magnetization curve of the magnet and apply only when the magnet is so used. Due to hysteresis (see H&R 37-6), a given current through the coils produces a unique field only if the history in establishing this current is identical from one time to the next. The best procedure to use is first to set up the maximum current in the coils. Then reverse this current by means of the reversing switch. Reduce the current by perhaps one half and again reverse the current. Proceed by reducing and reversing the current until the current is almost zero. In this way the field at zero current is reduced arbitrarily closely to zero and a unique starting point is established. The magnet calibration corresponds to a continually increasing coil current from the zero field, zero current point. Once a given current is established, it may not be decreased without destroying the calibration. Each time reduction of the field is necessary, the demagnetization procedure must be repeated.
3. Measurements. Establish a field of some 1000 to 1700 gauss and determine its polarity by means of a compass. The current in the magnet circuit must not exceed 1.9 amps!! With a current of some 20 ma to 300 ma in the Hall probe, measure the potential difference across the Hall effect sample. Vary both the current and magnetic field to establish the constancy of R and obtain a best value from your data. Evaluate the sign and density of charge carriers in the sample of indium arsenide.

Note: Consider the physical significance of your value for n .

ALPHA PARTICLE ABSORPTION

The intensity of a collimated beam of alpha particles (helium nuclei) passing through matter is reduced in two ways: The particles may be scattered out of the beam, or they may be absorbed in the material. The scattering process was studied in the Rutherford scattering experiment. Absorption is observed in this experiment.

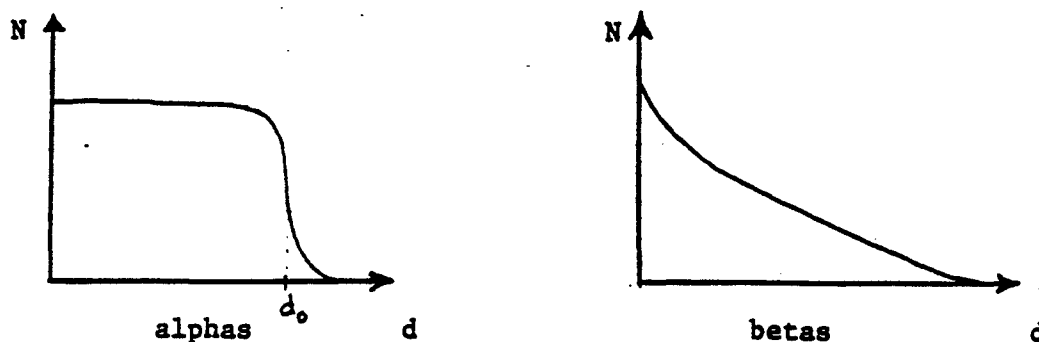
The primary energy-loss mechanism for absorption of any charged particle in passing through matter is electron excitation, i.e., energy transferred to an electron of the matter in raising it to an excited state. The probability of this transfer is strongly dependent upon the speed of the charged particle. A slowly moving particle "spends more time" in the vicinity of any given electron than a rapidly moving one and is more likely to raise it to an excited state. (See Appendix) This accounts for the very short penetration, or range, of naturally occurring alpha particles compared to the range of electrons from typical beta emitters. The energies of alpha particles and of beta particles (electrons) as a function of v/c is indicated by the following graph:



For typical values of 5 Mev alphas and 0.5 Mev betas the ratio of electron to alpha speeds is ~ 17 . The range of a 5 Mev alpha particle in aluminum is approximately 0.02 mm; that of a 0.5 MeV electron is some 30 times as great.

Alpha and beta particles also differ, of course, in charge and mass. The greater charge of the alpha particle increases the probability of its excitation of a particular electron. Its greater mass, on the other hand, decreases the percent of energy which can be transferred in a given collision. The fractional energy transfer from a particle of mass M to a particle of mass m in a classical collision is of the order m/M . For a beta particle colliding with an electron this ratio is 1. For an alpha particle it is 1.4×10^{-4} . The alpha particle must undergo a great many collisions to alter its energy significantly. Its trajectory in matter is thus analogous to that of a particle in a viscous medium--aside from the occasional Rutherford scattering off the nucleus, the α -trajectory is quite straight. The trajectory of an electron on the other hand is analogous to that of a billiard ball; that is, the incident electron can be scattered through large angles. Assume you have a collimated, monoenergetic beam of particles (α or β) incident on a thin absorber that lets most of the particles pass through. Since the trajectories of all alpha particles

in the absorber are nearly the same, the energies and directions of the emerging alphas are also essentially the same. On the other hand, electrons would take very different paths through the absorber so that the energies and directions of the emerging electrons would vary widely. Plotting the number of particles passing through an absorber as a function of absorber thickness, we have the characteristic curve.



The deviation of the alpha particle curve from a vertical drop to zero at the end of their range is known as "straggling." The straggling of beta particles is so large as not to deserve the name.

Several other processes are involved in the absorption of alpha particles. Energy is transferred to nuclei in Rutherford elastic scattering. Occasionally inelastic scattering from nuclei occurs in which the nucleus is displaced from its normal position, introducing a lattice defect in crystals. A sufficient concentration of such defects is observable as a halo surrounding inclusions of uranium minerals in old micas. At low speeds the alpha particle may pick up electrons to become a singly ionized or neutral helium atom with a consequent decrease in energy loss. All of these processes are involved in alpha particle absorption and, together with the basically statistical nature of electron excitation, contribute to straggling. Excitation of electrons, however, is the primary absorption process.

Experiment

The apparatus to study alpha particle absorption is a modification of that used in the Rutherford scattering experiment. The annular gold scatterer is covered with a brass disc, in the center of which is a small hole. Only those alphas from the americium 241 source which pass through this hole may reach the silicon detector (see Exp. 3). The source-to-detector distance L (which is given for your apparatus) remains constant throughout the experiment. The absorber is air. The amount of absorber in the alpha particle path is adjusted by varying the air pressure within the apparatus.

Pump the system down to "zero" pressure, as read on the manometer, to obtain the counting rate of the detector with no absorber in the alpha particle path. The pumping system is so arranged that you may now shut off the pumping line from the vacuum pump to the apparatus. With this valve closed, a "bleeder" valve is briefly cracked open to admit a small amount of air to the apparatus. The air in the apparatus may thus be raised to any desired pressure less than atmospheric. Always keep a pressure differential of at least some 5 cm. of mercury, however, to maintain the detector seal to the apparatus. The pressure may be reduced at any time by reopening the valve to the vacuum pump with the bleeder valve closed.

Determine the counting rate of the detector as a function of air pressure in the apparatus at sufficiently many points that a plot of counting rate N vs. pressure is well defined from zero pressure to that at which the counting rate is essentially zero. This is the absorption curve as a function of air pressure p . It is useful to express the absorption curve in terms of the path length in air at standard pressure rather than in terms of the pressure of air for a fixed path length. This conversion can be made easily by employing the ideal gas law, $pV/T = \text{constant}$. Assume the temperature T is a constant and $V = A\ell$, where V is the volume of a cylinder of air with fixed cross-sectional area A and a variable length ℓ . Then $p\ell = \text{constant}$ and we have

$$d = (L/P_0)p$$

where p is the apparatus pressure, L is the apparatus path length, P_0 is standard atmospheric pressure (760 mm Hg) and d is the path length in air at standard pressure. Use this equation to re-express the pressure scale on your plot in terms of d .

The range d_0 is defined as the path length of air (at standard pressure) required to stop half the alpha particles. Determine d_0 from your data. Then use the range vs. energy curve on p. 5-4 to obtain the energy of the alpha particles.

Another way to characterize the absorption process is to give the number of alpha particles stopped per unit path length of air as a function of path length. The number stopped per unit length is just $|\Delta N|/\Delta d$. Plot $|\Delta N|/\Delta d$ vs d (or $|\Delta N|/\Delta p$ vs p). Where do most of the alpha particles stop? The width of the curve is a measure of straggling. From this plot obtain some dimensionless number that characterizes the amount of straggling. Define this number precisely.

The ranges of alpha particles of a given energy in different materials are approximately related by the semiempirical Bragg-Kleeman rule. If ρ_0 and A_0 are the density and atomic weight of one material and ρ_1 and A_1 Those of a second, then according to this rule

$$R_1 / R_0 = \rho_0 \sqrt{A_1} / \rho_1 \sqrt{A_0}$$

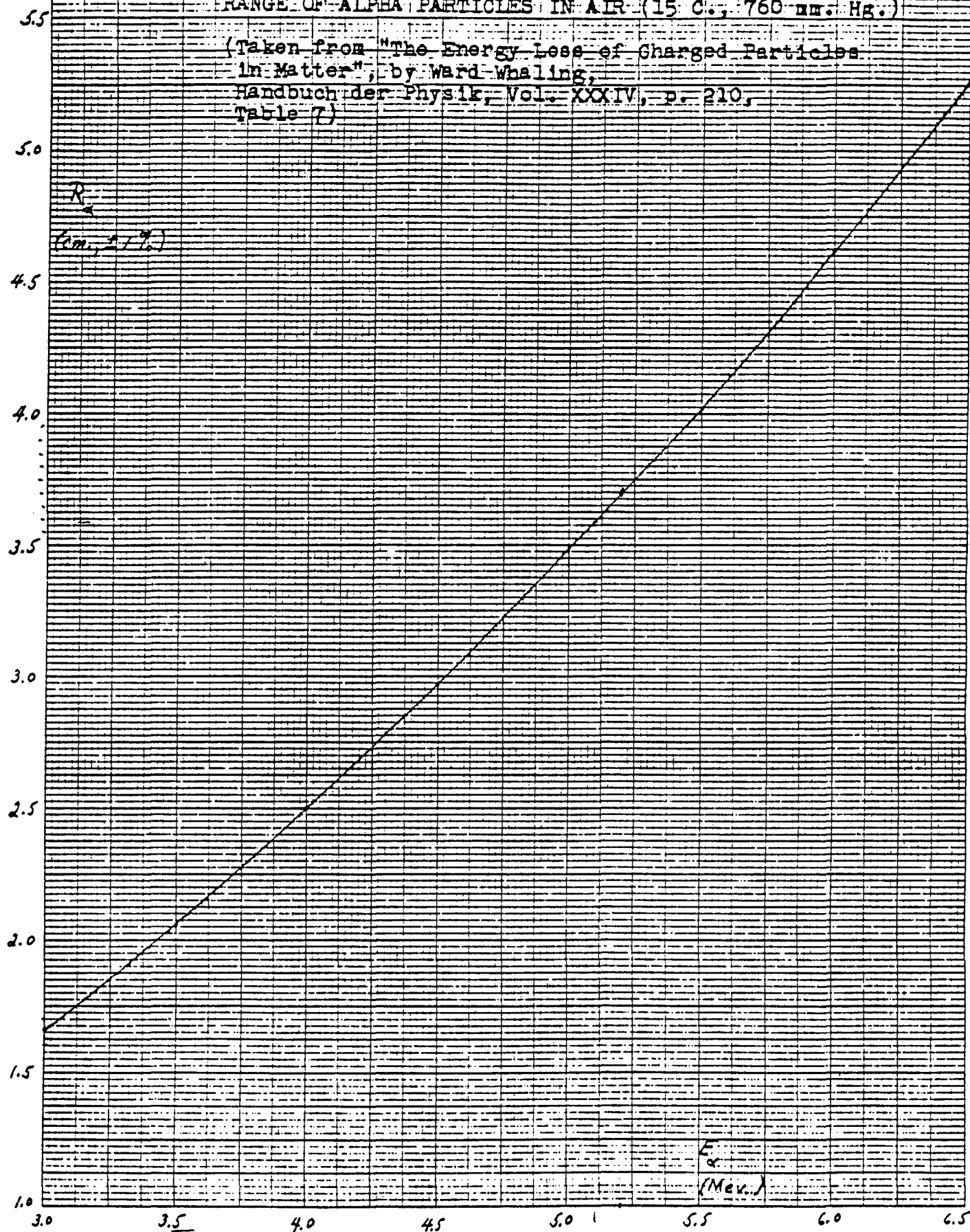
where R_0 and R_1 are the ranges in the two materials. For air at 20°C and standard pressure $\rho_0 = 1.29 \times 10^{-3} \text{ gm/cm}^3$ and $\sqrt{A_0} = 3.82$. Calculate the range of these alpha particles in gold, the scattering material used in the Rutherford scattering experiment.

RANGE OF ALPHA PARTICLES IN AIR (15° C., 760 mm. Hg.)

(Taken from "The Energy Loss of Charged Particles in Matter", by Ward Whaling, Handbuch der Physik, Vol. XXXIV, p. 210, Table 7)

R
(cm, $\pm 1\%$)

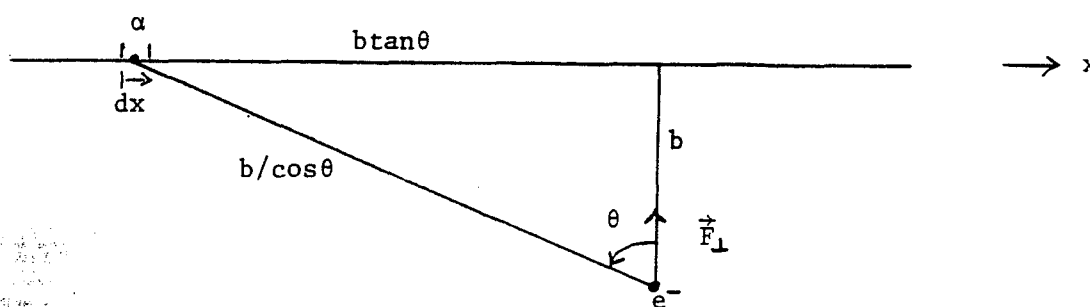
E
(Mev.)



Appendix: Energy loss of an alpha particle passing by an electron.

The initial kinetic energy of a typical alpha particle is about 5 MeV, and its speed is about .05 c, slow enough that it can be treated nonrelativistically here. Since the mass of an alpha particle is about 7000 times greater than that of an electron, momentum conservation tells us it is safe to assume that a collision of an alpha particle with an electron has essentially no effect on the direction of the α trajectory.

In the figure below, the α trajectory is a straight line. It passes by an electron whose perpendicular distance from the trajectory ("impact parameter") is b . The electron is attracted to the α by the Coulomb force acting along the line joining them. The net momentum transferred to the electron by the passing α is in the direction perpendicular to the α trajectory.



The perpendicular component of the momentum transferred to the electron in the time interval dt during which the α moves a distance $dx = vdt$ is

$$dp_{\perp} = F_{\perp} dt = F_{\text{coulomb}} \cos \theta dt$$

$$dp_{\perp} = \left[\frac{1}{4\pi\epsilon_0} \frac{Ze^2}{(b/\cos\theta)^2} \right] \cos \theta (dx/v)$$

(where $Z = 2$ for an alpha particle). But $x = b \tan \theta$, so that $dx = -b \sec^2 \theta d\theta$, where the minus sign indicates that θ decreases as x increases.

$$\therefore dp_{\perp} = -\frac{1}{4\pi\epsilon_0} \frac{Ze^2}{b^2} \cos^3 \theta \left(\frac{b}{\cos^2 \theta} \right) \frac{d\theta}{v} = \frac{-1}{4\pi\epsilon_0} \frac{Ze^2 \cos \theta}{bv} d\theta$$

If we assume that the electron does not move appreciably during the time the particle is in its vicinity, then the total impulse given to the electron is just

$$\Delta p_{\perp} = -\frac{1}{4\pi\epsilon_0} \frac{Ze^2}{bv} \int_{+\pi/2}^{-\pi/2} \cos \theta d\theta = \frac{1}{4\pi\epsilon_0} \frac{2Ze^2}{bv}$$

The energy lost by the α to the electron is then

$$\Delta E_e = \frac{\Delta p_{\perp}^2}{2m_e} = \left(\frac{1}{4\pi\epsilon_0} \right)^2 \frac{2Z^2 e^4}{b^2 m_e v^2}$$

which shows that the slower the α , the greater the energy transferred to the electron.

BETA AND GAMMA ABSORPTION

In this experiment you will study the absorption of beta particles (electrons) and gamma rays (photons) in aluminum and lead. As was pointed out in Experiment 5, typical beta particles travel much faster than typical alpha particles and as a result usually travel considerably farther before being absorbed. On the other hand, the mass of the beta particle is equal to the mass of the electrons which scatter it, so that the actual path of the beta particle traversing an absorber is much greater than a straight line trajectory through it. The range of beta particles is, accordingly, less well defined than that of the much more massive alpha particles, which travel nearly straight paths in the absorber. There is one other important distinction between beta and alpha particles: Both result from nuclear transitions of well-defined energies. In the case of alpha emission, the final state of the system has only two particles, the alpha particle and the recoil nucleus. Therefore, momentum and energy conservation fix the alpha energy. In contrast, beta decay results in a three-body final state, since a neutrino (actually an "anti-electron-neutrino") is also present. As a result the beta energy is not fixed but can have any energy from zero up to the maximum transition energy. (The actual distribution of the beta energy gives information about the mechanism of the decay process, a topic which is beyond the scope of this experiment, but which is studied in senior lab.)

There is one important similarity of alpha and beta particles. Both are charged and lose energy as a result of long-range Coulomb interactions with electrons (primarily) in the absorbing material. On the other hand, gamma rays (photons) are neutral; they do not lose energy by long-range forces. There are two mechanisms whereby gamma rays with energies less than 1 MeV are removed from a collimated beam, the photoelectric effect and Compton scattering. In the photoelectric effect the photon is absorbed in a collision with a bound electron, resulting in an ejection of the electron (called a "photoelectron") from the atom. (The photoelectron then loses energy by Coulomb scattering.) Compton scattering is the elastic scattering of a photon by an electron. In this case the recoil photon scatters out of the collimated beam, while the recoil electron loses energy in the usual manner.

The photoelectric effect and Compton scattering are both "one-shot" processes of removal, in contrast to the slowing down of a charged particle by Coulomb scattering. The probability that a photon present at a distance x in an absorber is absorbed or scattered out of the beam in the interval x to $x + dx$ is proportional to dx . Thus the change in intensity in the interval dx is

$$dI = -\mu I dx$$

where μ , the "attenuation coefficient" is the constant of proportionality. Integrating,

$$I = I_0 e^{-\mu x}.$$

This exponential absorption law is quite distinct from the absorption behavior of alpha and beta particles.

If x is measured in units of length [cm] then $\mu[\text{cm}^{-1}]$ is called "linear attenuation coefficient." As different absorbers can have very different densities, it is convenient to divide the linear

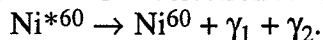
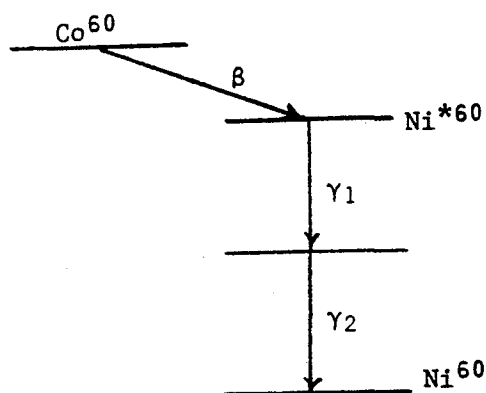
attenuation coefficient by the density of the absorber ρ to get the "mass attenuation coefficient" μ/ρ [cm²/gm]. In this case

$$I = I_0 e^{-(\mu/\rho)(\rho x)}$$

and the absorber thickness is given as ρx [gm/cm²].

Decay schemes

A typical source of beta particles and gamma rays for this experiment is radioactive cobalt 60. Its decay scheme is shown below. Symbolically, $\text{Co}^{60} \rightarrow \text{Ni}^{*60} + \text{electron} + \text{antineutrino}$



The electron and neutrino share the 310 Kev between the excited state of nickel, Ni^{*60} , and the ground state of Co^{60} shown. The electron energies are thus distributed from 0 to an upper limit of 310 Kev. The excited nickel decays to the ground state by emission of two gamma particles, γ_1 and γ_2 , of energies 1.17 and 1.33 Mev respectively.

Look up the decay schemes of the sources at your station in the Table of Isotopes supplied.

Apparatus

Betas and gammas are detected by a Geiger tube (see description at your lab station) situated above the radioactive source which sits in a lead shield. Calibrated aluminum or lead absorbers are stacked between the source and the Geiger tube. The thinner absorber foils are fragile. Handle them only by the plastic rings upon which the foil is mounted. The proper operating potential for the Geiger tube is given at each station.

Measurements

Study the absorption of beta particles first. Determine the counting rate with no absorbers placed between the source and detector. Absorption by the air path, Geiger tube window and sample cover is still present and should be accounted for. The density of air at 1 atmosphere and 20° C is 1.3 mg/cm³, so that its "thickness" is 1.3 mg/cm² per cm of path. The Geiger tube window thickness is 1.5-2.0 mg/cm² and the sample cover thickness is given at your station. Place various thicknesses of aluminum above the source and record the counting rate vs absorber thickness. Include errors due to counting statistics.

If the radioactive source of beta particles is also a source of gamma rays, the absorption curve for beta particles will reach nearly a constant counting rate with increasing thickness of the aluminum absorber. At this point, essentially all of the betas have been absorbed while the

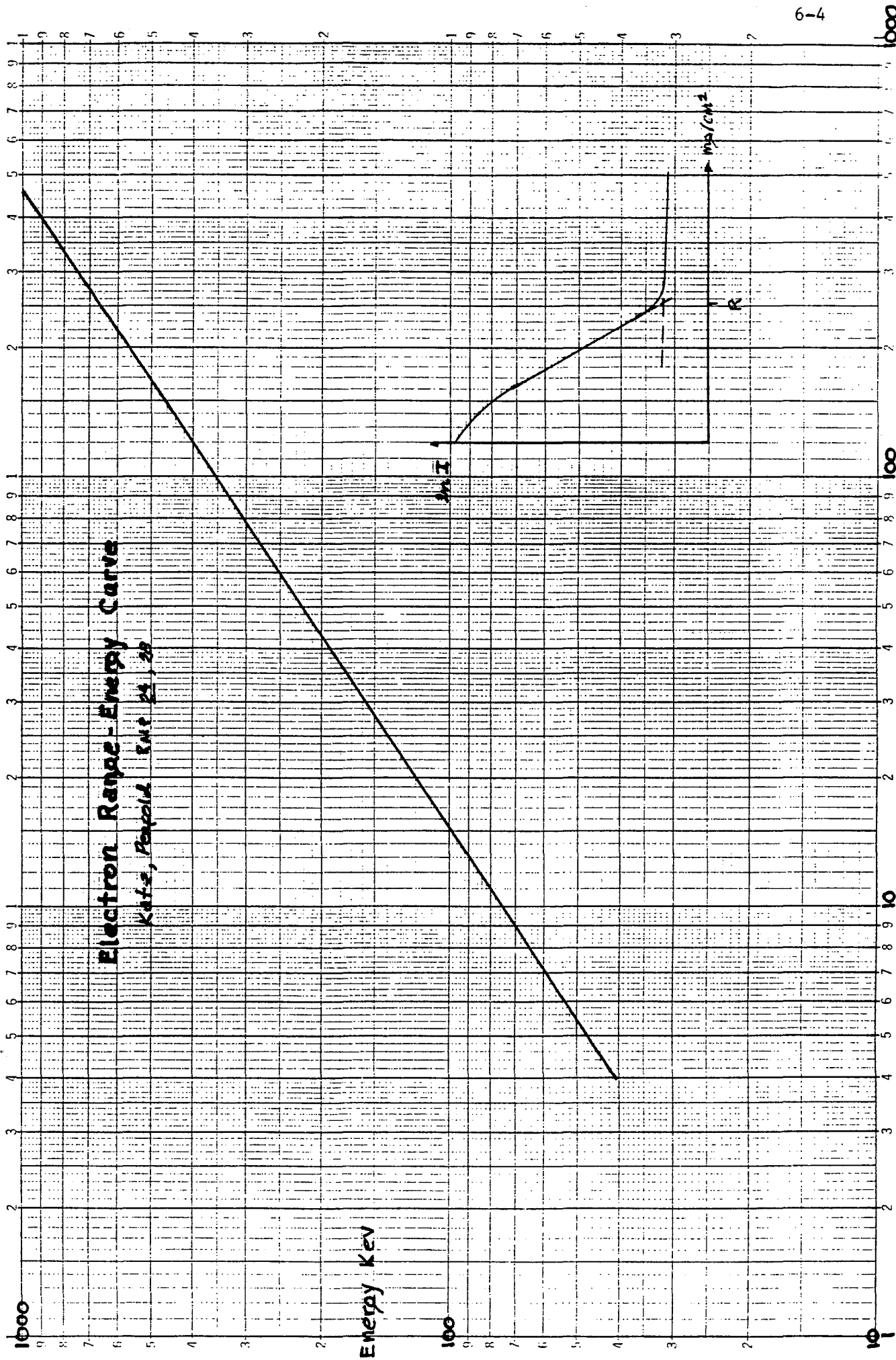
gamma rays are still only slightly attenuated. Obtain sufficient data to estimate the maximum thickness of absorber (including air path, etc.) traversed by the betas. The most useful way to view the data is to plot the logarithm of the counting rate vs. the absorber thickness (not the log of the absorber thickness). Obtain the maximum absorber thickness from the intersection of the best possible straight-line extrapolation of the beta curve with the straight-line extrapolation of the gamma (or background) curve. From this result and the "Electron Range-Energy Curve" on the next page, estimate the upper limit of the beta particle energy spectrum.

Study the absorption of gamma rays by placing lead absorbers above the source. Plot the logarithm of the counting rate vs. absorber thickness to determine the attenuation coefficient. Then use the graph on "Gamma Ray Absorption in Lead" to estimate the gamma ray energy.

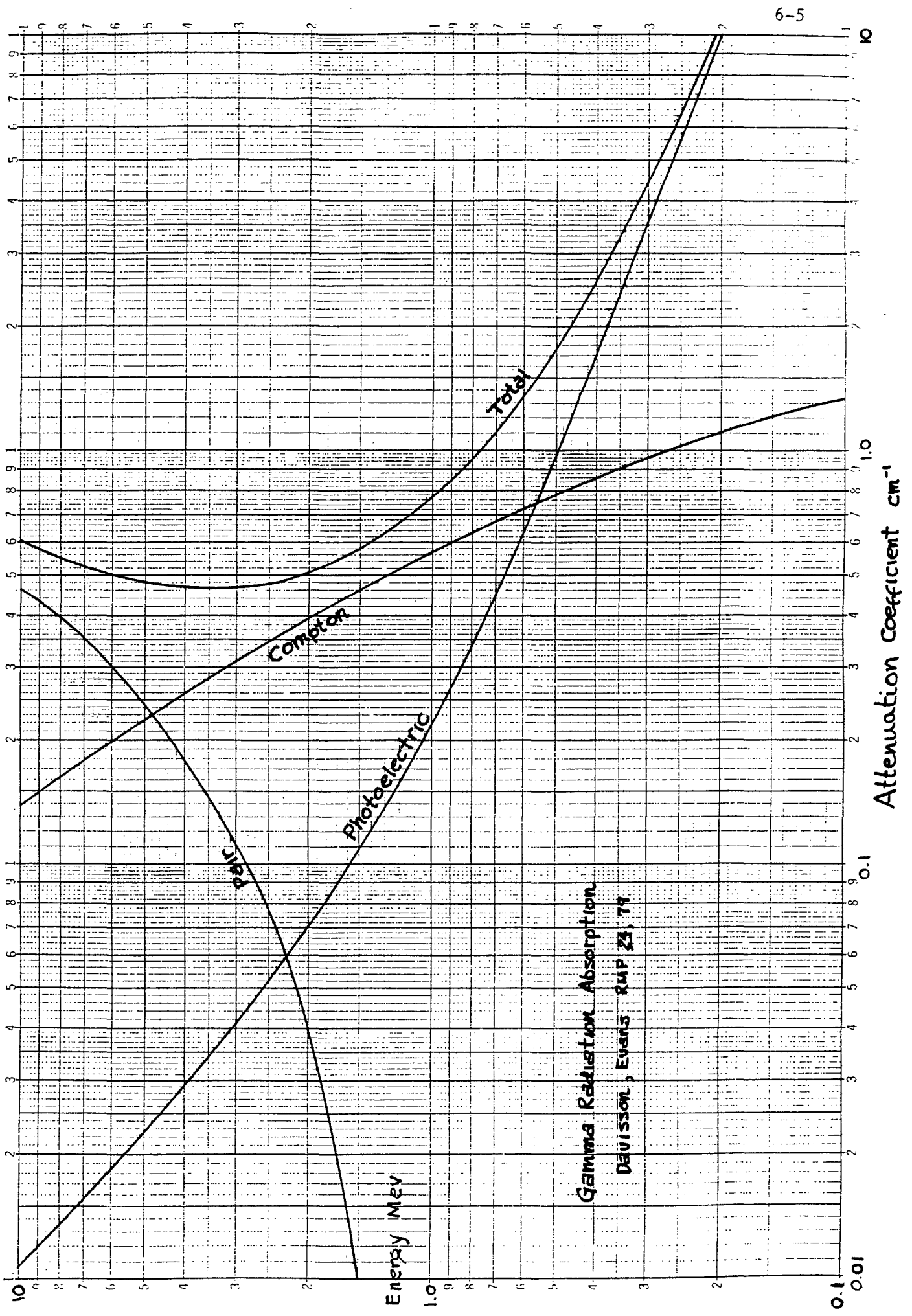
In comparing your estimates of beta and gamma energies with literature values, think carefully about possible sources of systematic error.

Electron Range-Energy Curve

Kat-3, Rayfold Rm 24, 25



Range mg/cm²



GAMMA RADIATION INTERACTIONS

Introduction

Electromagnetic radiation of wavelength greater than $\sim 0.01 \text{ \AA}$ interacts with matter in just two ways: the photoelectric effect and Compton scattering. Both are nonclassical and most simply described as the interaction of a particle--the photon, or gamma ray--with an atom.

Both interactions remove an electron from the atom, and each is observed by detecting this electron. The identifying feature of the photoelectric interaction is that the electron emerges with a single energy $E = hc/\lambda$. since the photon is destroyed in the interaction then, for energy conservation, E is the photon energy. Compton scattering, on the other hand, is interpreted as elastic scattering of the photon of energy E and momentum $p = h/\lambda = E/c$ from an atomic electron. If the photon is scattered by an angle θ from its original direction, then its new wavelength λ' is related to its original wavelength λ by the Compton formula

$$\lambda' - \lambda = \frac{h}{mc}(1 - \cos\theta) \quad (1)$$

You may readily show, then, that the electron acquires the energy

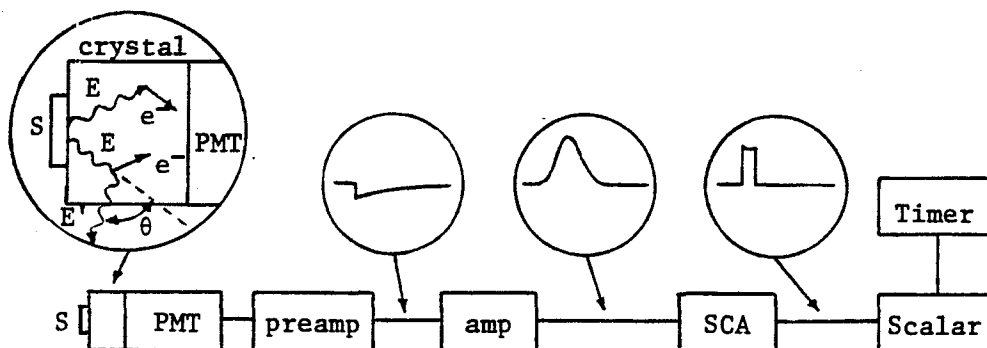
$$E_e = \frac{E}{1 + \frac{mc^2}{E(1 - \cos\theta)}} \quad (2)$$

where mc^2 for an electron is 511 KeV.

The experiment is performed with radiation from a radioactive source such as cesium 137 incident upon the atoms in a 2" diameter by 2" thick crystal of sodium iodide. The radiation from cesium 137 consists of gamma rays of energy 662 KeV. Compton and photoelectrons freed from atoms of the crystal by this radiation rapidly come to rest within the crystal, converting their energy into that of low energy photons. In sodium iodide, these secondary photons are in the visible spectrum and are detected by a photomultiplier tube. The photomultiplier converts them into an electrical pulse of amplitude proportional to the total energy of the secondary photons--hence also proportional to the initial electron energy. By observing the amplitude distribution of these pulses, we determine the energy distribution of electrons freed from atoms of the crystal by interactions with the incident radiation.

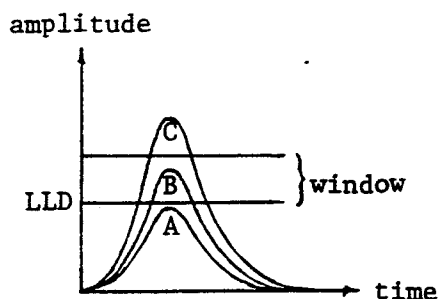
Experiment

The apparatus is shown schematically below:



The source S is taped to the front of the sodium iodide crystal. The enlargement illustrates photoelectric and Compton interactions within it. Secondary photons are generated as the electrons e^- come to rest. These photons are detected by the photomultiplier tube PMT mounted in a common housing with the crystal. The preamplifier generates a negative output pulse as shown in the inset with amplitude proportional to the energy of the Compton or photoelectron feed within the crystal. The amplifier then inverts, shapes and amplifies the pulse as shown.

The amplifier output is directed to a single channel analyzer SCA. This is the instrument with which the pulse amplitude distribution is determined. You will control two settings of the



SCA—its lower level discriminator LLD and its window. The function of these controls is shown in the figure below. A, B, and C are three pulses from the amplifier to the SCA. The controls set the height of the line LLD and the width of the gap labeled "window." As set, only pulse B will trigger an output pulse from the SCA. The maximum amplitudes of A and C lie outside the window and neither pulse is sent on to the scalar. Were the LLD lowered so that the window embraced only pulse A, then only pulses of this maximum amplitude would be registered by the scalar. Were the window

opened to include the maxima of both B and C, then both of these pulses would be registered. The scalar is started and stopped by a timer and counts the number of pulses it receives from the SCA within this time which satisfy the condition:

$$\text{LLD} \leq \text{maximum pulse amplitude} \leq \text{LLD} + \text{window}$$

We wish to observe the amplitude distribution of pulses generated by electrons from gamma interactions within the sodium iodide crystal. First, connect an oscilloscope to the output of the

amplifier. You will see a broad amplitude distribution, with a bright band of pulses of nearly the same maximum amplitude. These are generated by photoelectric interactions in the crystal. Set the amplifier gain so that these pulses have ~5-8 volts maximum amplitude. Remove the scope and reconnect the amplifier to the SCA. Set the SCA window¹ to 0.2 volts and the LLD somewhat below the maximum voltage of the bright band observed on the scope. Set the timer for 10 sec or so and count the number of pulses received by the scalar at this setting of the SCA. Advance the LLD by 0.2 volts, leaving the window fixed, and count again. Proceed in this way through the "photopeak." You now know how to use the apparatus.

For Cs 137, the photopeak observed above occurs at 662 KeV. Since each component of the apparatus is linear, this number calibrates the entire voltage range of the LLD in electron-volts. You are now prepared to study the entire energy spectrum of electrons resulting from photoelectric and Compton interactions of gamma radiation from Cs 137 with atoms of the sodium iodide crystal. Start with the LLD at zero volts and proceed through the photopeak. Plot as you go! Where the distribution is quite flat, you should increase the increments by which the LLD is advanced. Where it changes rapidly, you may wish to decrease them. Set the timer to obtain good statistics. Remember that the uncertainty in the number N of pulses counted in a given time interval is $\pm\sqrt{N}$.

Things to observe

Classically, one would expect no structure in the pulse amplitude distribution at all. The prominent peak you observe attests to the nonclassical photoelectric interaction first accounted for by Einstein.

The Compton interaction produces electrons of energy from zero, $\theta = 0$, to a maximum for $\theta = \pi$ (equation 2). The maximum defines the "Compton edge." Calculate where you expect the edge to appear and locate it in your experimental distribution. You will probably also observe a rather broad peak at the energy $E - E_e$. This is the energy of a gamma ray which has scattered at $\theta \cong \pi$. This occurs for gammas emitted by the source away from the crystal, which are then scattered from the table, floor, walls, etc. back into the crystal. The peak may be enhanced by placing an aluminum plate immediately behind the source.

You should also observe a narrow peak at an energy of ~30 KeV. The radiation responsible is an x-ray from barium, the decay product of cesium within the source. Look up the known energy of this x-ray and compare it to your result. You may wish to place a lead brick behind the source and observe x-rays from lead (~70 KeV) which arise with each photoelectric interaction in the lead.

¹In "window" mode, the Window pot goes from 0-1 v, while the Lower Level pot goes from 0-10 v.

BARRIER PENETRATION

A striking consequence of quantum mechanics is the prediction that a particle of total energy E located in a potential well of depth $V_0 > E$ has a finite probability of escaping if the walls of the potential well have a finite thickness. This phenomenon, known as barrier penetration or tunneling, is not uncommon at the atomic or subatomic scale; for example, α decay occurs via tunneling of the α particle through the Coulomb barrier of the radioactive nucleus (see Section 16-2 of Eisberg and Resnick). While barrier penetration is hardly commonplace on the macroscopic scale, it can be seen; in fact, barrier penetration is a property of both classical and quantum mechanical wave motion.

An optical analog of barrier penetration, known as "frustrated total internal reflection," is described formally by the same equations that describe quantum mechanical tunneling. In this phenomenon, a light beam traveling through glass (or any other transparent medium with an index of refraction $n > 1$) is incident on the glass-air interface. For sufficiently small angles of incidence, the light is partly reflected and partly transmitted into the air. But for angles of incidence greater than the "critical angle" $\sin^{-1}(1/n)$, the beam is totally reflected back into the glass; no light is transmitted into the air. The oscillating electromagnetic field of the light does not stop precisely at the interface, however; it extends some distance into the air. If another piece of glass is brought close enough to the interface, this electromagnetic field can then propagate away from the interface (thus the total internal reflection is "frustrated"). The trick is getting the second piece of glass close enough, to within about a wavelength of the interface. Unless the interface is very flat, the effect won't occur; in any case, the gap is so small as to be invisible.

One can change the scale of electromagnetic radiation to the microwave region, where wavelengths are on the order of cm. Then this phenomenon can be easily observed. For radiation with wavelengths of a few cm, polyethylene becomes a good substitute for glass; it is almost transparent to microwaves and has an index of refraction very similar to that of glass for optical frequencies. A microwave beam traveling through a polyethylene block and incident on the polyethylene-air interface at an angle of 45° undergoes total internal reflection, provided the interface is isolated. Again, there is an oscillating electromagnetic field extending into the air beyond the interface, as you will see. If another polyethylene block is brought close enough to the interface, it should allow a transmitted wave to propagate away from the interface. You will study this phenomenon.

In the experiment there are two 45° - 45° - 90° polyethylene prisms arranged so that the two hypotenuse faces can be brought close together. A microwave beam is incident on the first prism perpendicular to one base, travels through the prism and strikes the hypotenuse at 45° . If the perpendicular separation of the two prisms is d , then the fraction of the microwave radiation intensity that can penetrate the gap between the prisms (T) is given by

$$T = (1 + \alpha \sinh^2 \beta d)^{-1}$$

The form of this equation is identical to that seen for quantum mechanical barrier penetration (see Section 6-5 of Eisberg and Resnick). The coefficients α and β can be obtained from classical electromagnetic theory. For the geometry of this experiment one obtains¹

¹See, e.g., J. Strong, Concepts of Classical Optics (1958), Section 6-9

$$\alpha = \frac{(n^2 - 1)^2}{n^2(n^2 - 2)}$$

$$\beta = \frac{2\pi}{\lambda} \sqrt{(n^2 - 2)/2}$$

where n is the index of refraction of the polyethylene and λ is the wavelength in air.

Preliminary Measurements

In order to predict the intensity of the microwave radiation transmitted across the gap, you need to know the microwave wavelength and the index of refraction of polyethylene. And there is one more subtle question, namely, does the detector measure the intensity of the microwave radiation? That is, does the detector respond linearly to the square of the microwave electric field strength? You will perform some preliminary measurements to determine these three parameters.

Transmitter and receiver The microwave transmitter operates at 10.5 GHz. The microwaves emitted from the horn are polarized parallel to the long axis of the Gunn diode (the slender shiny cylinder located at the base of the horn). While the transmitter can be rotated to change the polarization axis, for this experiment the Gunn diode should be kept vertical (0 on the scale). The microwave receiver consists of a detector diode mounted similarly at the base of the detector horn. The diode responds only to the component of the microwave signal that is parallel to the diode axis. There are four amplification ranges and a variable gain control on the receiver. Always start at the least sensitive range (30X) to avoid damaging the electronics.

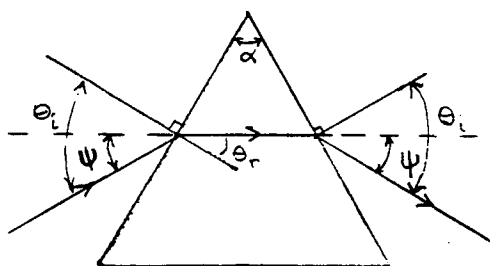
Wavelength A good way to measure the wavelength is to use a Fabry-Perot interferometer. Follow the procedures in the PASCO Instructions and Experiments Manual, Experiment 9, p. 26. Compare your result with the expected value for 10.5 GHz radiation.

Receiver Response You can check to what extent the meter reading on the microwave receiver is proportional to the intensity by seeing how the meter reading changes as the diode axis of the receiver is rotated relative to the polarization direction of the transmitted electric field (transmitter diode axis). If the meter responds directly to the electric field strength, then the meter reading should be proportional to $\cos \theta$, where θ is the angle of the detector diode relative to the E field. If the meter responds to intensity, then the meter reading should be proportional E^2 , hence to $\cos^2 \theta$. In fact, the detector diode is a nonlinear device, so that the way the meter responds can vary with the strength of the field. To test the meter in the relevant range, you should separate the transmitter and receiver by about 2.5 m, roughly the same distance you will be using in the barrier penetration experiment. (The goniometer arm on which the transmitter and receiver were mounted for the wavelength determination should be removed from the table to minimize spurious reflections.) Adjust the detector position to get a maximum signal when both transmitter and receiver diodes are vertical. Set the meter reading to full scale. Then rotate the receiver in 15° increments up to 90° and record the meter readings. Compare with $\cos \theta$ and $\cos^2 \theta$. The meter response should be quite close to $\cos^2 \theta$ (intensity) at this separation. If it is not, see your instructor.

Index of refraction Light (or microwave radiation) incident on a prism is refracted on entering and leaving the prism. If the prism is oriented so that the angle with which the beam leaves the prism (where as usual the angle is measured relative to the normal to the surface it is exiting) is the same as the angle at which it enters (relative to the normal to the front surface)--see the figure--then the index of refraction is given by

$$n \equiv \frac{\sin \theta_i}{\sin \theta_r} = \frac{\sin(\psi + \alpha/2)}{\sin(\alpha/2)}$$

where θ_i is the angle of incidence, θ_r is the angle of refraction, α is the apex angle of the prism, and ψ is defined as shown in the figure.



(Note: As part of your writeup for this experiment, you should derive this formula.) Two rotating goniometer arms are attached to the platform supporting the fixed polyethylene prism. (You may have to roll back the second polyethylene prism to see the second goniometer arm.) The angle scales marked for each arm correspond to the angle ψ in the figure above. Position the transmitter on one arm and the receiver on the other. Rotate the arms symmetrically relative to the 45° apex angle of the prism (i.e., both angles must be the same) and locate the angle ψ where the receiver signal is a maximum. Use this to determine the index of refraction of the prism.

Barrier penetration measurement

Remove the transmitter and receiver from the goniometer arms and rotate the arms so that they are parallel to the base of the prism. Use the pegs provided to fix these arms in position. Now roll the second prism all the way up to the first prism. Place the receiver in the guides on the movable platform behind the second prism. (The separation of the prism and the receiver should be about 30 cm to the base of the receiver horn.) Place the source about 190 cm from the front face of the fixed prism and align it carefully to give a maximum reading on the receiver meter. Slide the receiver forward and backward a few cm in the guides to maximize the signal. Set the sensitivity for full-scale reading when the two prisms are touching. Now roll the prism back. You should see the meter reading drop quickly, with essentially 0 reading for a separation of several cm. If the reading does not drop to at most 5-10% of the initial reading, you need to realign the source and detector and look for any causes of extraneous reflections. With the second prism still several cm away, adjust the position of the second receiver, located to detect the beam reflected from the hypotenuse of the fixed prism. This detector should be about 30 cm from the fixed prism. Adjust its position for a maximum meter reading and set this to 1 when the movable prism is "far" away. Now roll the second prism toward the fixed prism and note the meter readings on the two receivers. Describe qualitatively what you see.

Since the receiver monitoring the reflected beam can produce spurious reflections which affect the transmitted beam receiver, it should be removed for the rest of the experiment. Be sure to turn off the receivers after you are finished with them, as their batteries run down quickly. Recheck the transmitter receiver for the extreme positions of the movable prism, and if necessary readjust and reset before taking quantitative measurements. Vary the movable prism location, measure the perpendicular separation d of the prisms, and plot the resulting transmission coefficient T . On the same graph, plot the predicted transmission coefficient. Compare the two and comment.

PHOTOELECTRIC EFFECT

Background¹

Around the turn of the century, Philipp von Lenard, studying a phenomenon originally observed by Heinrich Hertz, showed that ultraviolet light falling on a metal can result in the ejection of electrons from the surface. This light-induced ejection of electrons is now known as the photoelectric effect. Einstein's explanation of this effect in 1905 (the year he also developed Special Relativity!) is one of the cornerstones of quantum physics.

According to the classical theory of electromagnetic fields, the intensity of a light wave is directly proportional to the square of the electric field of the wave. An electron in some material exposed to this light wave should feel a force proportional to this electric field. For an intense enough illuminating light, the electron should be able to gain sufficient kinetic energy to escape the material. The energy gained by the electron depends only on the intensity of the light (and the nature of the material), not on the wavelength.

That, however, is *not* what is observed experimentally. In a series of very careful experiments in the 1910's, Robert Millikan showed that the maximum kinetic energy $K_{\max}$ of the ejected electron is independent of the intensity but linearly dependent on the frequency ν of the incident light:

$$K_{\max} = h\nu - W_0, \quad (1)$$

where h is a constant and W_0 is the "work function" characteristic of the material. Millikan found experimentally that h is numerically equal to the constant Max Planck introduced in his explanation of blackbody radiation.

In fact, Einstein's theory of the photoelectric effect in 1905 (hypothesized before Millikan's experiments) predicted just such a relationship, with h being identical to Planck's constant. In this theory, light exists in individual quanta, or photons. The energy of a photon is given by its frequency, $E = h\nu$. In the photoelectric effect a photon is absorbed by an electron, which then acquires the energy lost by the photon. If the electron is right at the surface (so it doesn't lose any energy in inelastic collisions on the way to the surface), then the electron can escape, provided its kinetic energy is greater than the work function W_0 . Increasing the intensity of the incident light of a given frequency would simply mean that *more* electrons are produced with sufficient kinetic energy to escape; the maximum kinetic energy of the escaping electrons would remain constant. However, if the frequency of the incident light is so low that the photon energy is less than the work function then *no* electrons will have sufficient energy to escape the material². The simple linear relationship between photon frequency and energy thus predicts Millikan's results. Two Nobel Prizes were awarded for work done on the photoelectric effect - one in 1921 to Einstein for his theoretical explanation, and one in 1923 to Millikan for his experimental work on this effect and for his more famous experiments establishing the charge of the electron.

¹See, e.g., Robert Eisberg, Robert Resnick. Quantum Physics of Atoms, Molecules, Solids, Nuclei, and Particles. 2nd ed. (Wiley, New York, 1985) Ch. 2.

²For sufficiently intense illumination, it is, in fact, possible for two "sub-threshold" photons to be absorbed by a given electron, allowing it to escape the material, even though the individual incident photon energies are less than the work function. Such nonlinear effects require very intense laser beams.

Experiment

In this experiment you will determine the maximum kinetic energy of electrons photoejected from a metallic cathode in a vacuum tube under various illuminations. The maximum kinetic energy is determined by measuring the “stopping potential,” the minimum reverse potential V between the cathode and the anode which reduces the photoelectric current in the tube to zero. In this case

$$K_{\max} = eV, \quad (2)$$

where e is the magnitude of the electron charge. Substituting this expression for $K_{\max}$ into Eq. (1) and solving for the stopping potential V gives

$$V = \left(\frac{h}{e}\right)\nu - \left(\frac{W_0}{e}\right). \quad (3)$$

Thus a plot of V vs. ν should give a straight line with a slope of h/e and an intercept of $-W_0/e$.

The experiment consists of two parts. In the first you will study the effect of light intensity on the stopping potential and test the predictions of the classical theory of electromagnetic radiation. In the second you will look carefully at the effect of light frequency on the stopping potential as a test of the quantum theory.

The experimental apparatus, made by PASCO Scientific, consists basically of a mercury vapor light source, diffraction grating, and a photodiode tube and associated electronics. The light source/diffraction grating setup allows you to study five spectral lines, from the near ultraviolet through yellow. Read quickly through the PASCO lab manual to get familiar with the equipment and procedures. You should assume that the basic alignment of the apparatus has already been accomplished, so that you will only need to properly locate the grating and photodiode detector for optimal performance. *Consult with your instructor before you make any other alterations.*

Caution: The mercury vapor lamp is a strong source of UV light. Never look directly into the beam, and always use UV-absorbing safety glasses when the lamp is on.

Using the PASCO manual as a rough guide, study the dependence of the stopping potential on both the intensity and frequency of the illuminating light. Your final analysis should include a determination of Planck's constant and also the work function of the photocathode.³

³Note from Eq. (3) that h/e has the dimensions of volt-sec (V-s) and W_0/e has the dimensions of volts (V).

From these results you can directly express h in terms of eV-s and W_0 in terms of eV, where

1 eV $\equiv$ 1 electron – volt $\equiv$ (charge of electron) $\cdot$ (1 volt). If you had some independent determination of electron charge, you could then give these results in terms of, say, joules rather than eV, but that's not necessary here.

THE CAVENDISH EXPERIMENT

Background

Isaac Newton's (1642 - 1727) theory of gravitation explained the motion of terrestrial objects and celestial bodies by positing a mutual attraction between all pairs of massive objects proportional to the product of the two masses and inversely proportional to the square of the distance between them. In modern notation, the law of universal gravitation is expressed

$$F = \frac{GMm}{r^2} \quad (1)$$

where M and m are the masses of the two objects, r the distance separating them, and G is the universal constant of gravitation. Newton was not particularly concerned to evaluate the constant of proportionality, G , for two reasons. First, a consistent unit of mass was not in widespread use at the time. Second, he judged that since the gravitational attraction was so weak between any pair of objects whose mass he could sensibly measure, being so overwhelmed by the attraction each feels toward the center of the earth, any measurement of G was impractical.

Notwithstanding Newton's pessimism, towards the latter half of the 18th century several scientists attempted to weigh the earth by observing the gravitational force on a test mass from a nearby large mountain. These efforts were hampered, however, by very imperfect knowledge of the composition and average density of the rock composing the mountain. Spurred by his interest in the structure and composition of the interior of the earth, Henry Cavendish in a 1783 letter to his friend Rev. John Michell discussed the possibility of devising an experiment to "weigh the earth." Borrowing an idea from the French scientist Coulomb who had investigated the electrical force between small charged metal spheres, Michell suggested using a torsion balance to detect the tiny gravitational attraction between metal spheres and set about constructing an appropriate apparatus. He died in 1793, however, before conducting experiments with the apparatus.

The apparatus eventually made its way to Cavendish's home/laboratory, where he rebuilt most of it. His balance was constructed from a 6-foot wooden rod suspended by a metal fiber, with 2-inch-diameter lead spheres mounted on each end of the rod. These were attracted to 350-pound lead spheres brought close to the enclosure housing the rod, roughly as illustrated in the figure below. He began his experiments to "weigh the world" in 1797 at the age of 67, and published his result in 1798 that the average density of the earth is 5.48 times that of water. His work was done with such care that this value was not improved upon for over a century. The modern value for the mean density of the earth is 5.52 times the density of water. Cavendish's extraordinary attention to detail and to the quantification of the errors in this experiment has lead C. W. F. Everitt to describe this experiment as the first modern physics experiment. In this experiment you will use a torsional balance similar to Cavendish's to "weigh the earth" by determining a value for G . *

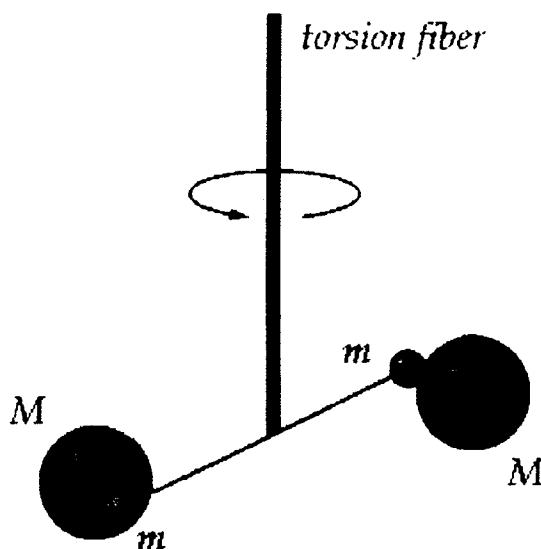
* In 1998 the accepted value for G was known to only 0.15% precision, a surprisingly crude number, reflecting the miniscule forces involved. In May 2000 in an experimental *tour de force*, Jens Gundlach and Stephen Merkowitz of University of Washington improved on that precision by a factor of 100, finding a value of $(6.67390 \pm 0.00009) \times 10^{-11} \text{ Nm}^2\text{kg}^{-2}$.

Theory

The Cavendish torsional balance is illustrated in the figure at the right. Two small metal balls of mass m are attached to opposite ends of a light, rigid, horizontal rod which is suspended from a torsion fiber. When the "dumbbell" formed by the rod and masses is twisted away from its equilibrium position (angle), the fiber generates a restoring torque proportional to the angle of twist, $\tau = -\kappa\theta$. In the absence of damping, the dumbbell executes an oscillatory motion whose period is given by $T = 2\pi\sqrt{\frac{I}{\kappa}}$, where I is the rotational inertia of the dumbbell,

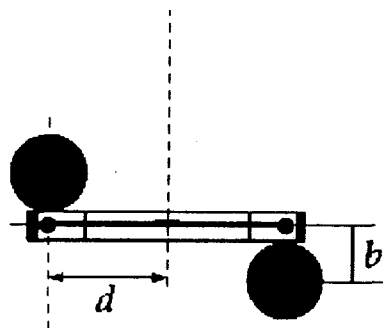
$$I = 2m\left(d^2 + \frac{2}{5}r^2\right).$$

In this expression, r is the radius of the small masses m , and d is the distance from the center of the rod to the center of one of the masses, and we have neglected the mass of the thin rod. Knowledge of m , d , and r , and a careful measurement of the period of oscillation T allows one to calibrate the torsion fiber, obtaining its spring constant κ . From κ and a measurement of the twist caused by the large masses M you can deduce the gravitational force between the masses, and hence G .



Gravitational Torque

When the large metal spheres are positioned as shown in the figure, the gravitational attraction between the large and small spheres produces a torque that rotates the dumbbell clockwise. Only the component of the force on each mass that is perpendicular to the horizontal bar produces a torque about the center of the rod. The magnitude of the torque between the two adjacent masses is given by $\tau_g = 2F_{\perp}d$, where the factor of 2 comes from the fact that the torque is equal on the two masses m . This torque displaces the equilibrium angle of the dumbbell by an amount given by $\tau = -\kappa\theta_0$.



Hence, if one can measure the equilibrium angle θ_0 very carefully, one can deduce the gravitational force that produces the torque and finally G .

Light Lever

Cavendish mounted a finely ruled scale near the end of the dumbbell, which he could read to one-hundredth of an inch resolution using a telescope. The telescope allowed him to remain outside the experimental chamber, thus eliminating air currents and his gravitational influence on the oscillator.

We will take advantage of a light lever to magnify the dumbbell's tiny rotation into an easily observed displacement on a far screen. The light lever is produced by bouncing a laser beam off a mirror mounted to the dumbbell. When light bounces off a mirror, the angle the incoming beam makes with the normal (perpendicular) of the mirror is equal to the angle the outgoing beam makes with the normal. If the mirror rotates through a small angle α , the outgoing beam rotates through the angle 2α , since both the incoming and outgoing angles change by the same amount. By measuring the motion of the laser spot on a far screen, and knowing the distance between the mirror and the screen, you can determine the angle α , from which you can infer the rotation of the dumbbell, θ .

Damping

In the absence of damping, the motion of the dumbbell is a sinusoidal oscillation with the period given by

$$T = 2\pi\sqrt{\frac{I}{\kappa}} \quad (2)$$

Viscous damping of the pendulum's motion caused by air resistance produces a drag torque proportional to the angular speed of the dumbbell. This causes the sinusoidal oscillation to decay exponentially, with a time constant τ that is long compared to the oscillation period. The motion is described by the function

$$\theta = \theta_0 + Ae^{-t/\tau} \sin(2\pi t/T + \phi_0) \quad (3)$$

where ϕ_0 is the initial phase of the motion, θ_0 is the equilibrium position, A is the amplitude of the motion, and τ is the time for the oscillation to fall to $1/e$ of its original value. (Note that this time has nothing to do with the torques, which, unfortunately use the same symbol!) By measuring $\theta(t)$ and fitting your data to this equation, you can determine both T and θ_0 , from which you can determine G .

Parameters

According to the Pasco manual, the parameters of the apparatus include the following.

Variable	Value
m	38.3 ± 0.2 g
r	9.53 mm
d	50.0 mm
b	46.5 mm

No uncertainties are given for the last three values. Since $m \propto r^3$, one could infer an uncertainty in r of 0.02 mm resulting from the uncertainty in m given above. Based on the precision of the value given for d one might reasonably assume an uncertainty of 0.1 mm in that value. The uncertainty in b depends on the accuracy of the horizontal alignment of the

pendulum (See the Pasco manual for the proper alignment procedure; your check of the alignment should give you an estimate of the uncertainty in b .)

Safety

Danger! The laser pointer that forms the light lever for this experiment is a class III laser capable of damaging retinas. ***Do not look directly into the beam.*** Please ensure that *nobody* looks into the beam. Note that it is safe to look at the diffuse spot the beam produces as it reflects from an object, such as a meter stick.

Procedure

1. See the instructions next to the apparatus for proper alignment of the oscillator. You should be sure that when the freely suspended dumbbell remains at rest, it is equidistant from the front and back faces of the enclosure. This alignment should be done with the large lead balls removed.
2. Carefully weigh the large lead balls. Place a styrofoam tray on the electronic scale and tare it. Then gently place the lead ball into the tray. ***If the lead balls are dropped, they will become misshapen, which will severely compromise the accuracy of the experiment.***
3. Lock the dumbbell using the screws on the bottom of the enclosure, then gently place the large lead balls in the armature. Rotate the armature until the balls just touch the sides of the enclosure. Gently lower the support screws until the dumbbell rotates freely. If it rotates so much that the dumbbell bounces off the sides of the enclosure, use the support screws to settle the motion.
4. Once the dumbbell oscillates freely, begin recording the position of the reflected laser spot as a function of time. Record at least two full periods.
5. Gently rotate the armature until the large balls once again touch the sides of the enclosure in the opposite orientation and record the position of the reflected laser spot as a function of time for at least another two periods.
6. If you have time you should finally return the armature to its original position and again record the position of the laser spot as a function of time for at least another two periods.
7. From the distance between the mirror and the screen on which you measured the laser spot position, you can deduce the angle of rotation of the dumbbell. As described above, fit a damped sinusoid to each set of data and extract the centers of rotation. From their difference and the data given in the parameters table above, you can deduce the value of G .

THE SPEED OF LIGHT

History

Galileo attempted to measure the speed at which a light beam traveled from a lantern on one hilltop to another, but was never able to observe a delay from which he could calculate the speed. In 1676, a Danish astronomer visiting the Paris Observatory directed by Giovanni Domenico Cassini (1625-1712) was studying the orbits of the Galilean moons of Jupiter in hopes of solving the longitude problem. He noticed a curious pattern in the moons' eclipses. The time of the eclipses was early by a few minutes when the earth was at points in its orbit closest to Jupiter, and a few minutes late six months later. Ole Roemer (1644-1710) correctly inferred that the shifts were due to the finite speed of light and in 1676 he estimated that speed as 140,000 miles per second (about 25% low).

Jean Bernard Leon Foucault (1819-1868) devised a way to make a terrestrial measurement of the speed of light using a rapidly rotating mirror. In the time it took a ray of light to travel from the surface of the rotating mirror to a distant fixed mirror, reflect back, and bounce again off the rotating mirror, that mirror turned a little bit and the reflected beam was deviated slightly from the path it would take when the mirror was not spinning. Knowing the rotation rate and the distance between mirrors, he measured the speed of light to be 2.98×10^8 m/s.

Other methods relying on measuring a distance and a time taken by light to cover that distance were developed and refined, leading to increasingly accurate measurements of the speed of light. Ultimately, the precision of time measurements outstripped that of distance measurements, which were tied to the "standard meter" defined as the distance between scratches on a platinum-iridium bar kept near Paris. In view of the success of Einstein's special theory of relativity, which holds that the speed of light is independent of the inertial reference frame in which it is measured, it was agreed in 1983 to define the value of the speed of light as 299 792 458 m/s, so that the length of the meter would be based on the defined value of c and the fundamental unit of time, the second.

In view of the accuracy of the method you will explore in this experiment, we will not adopt the current definition of the meter based on an assumed value of the speed of light, but will instead measure the speed of light in terms of a measured length and time.

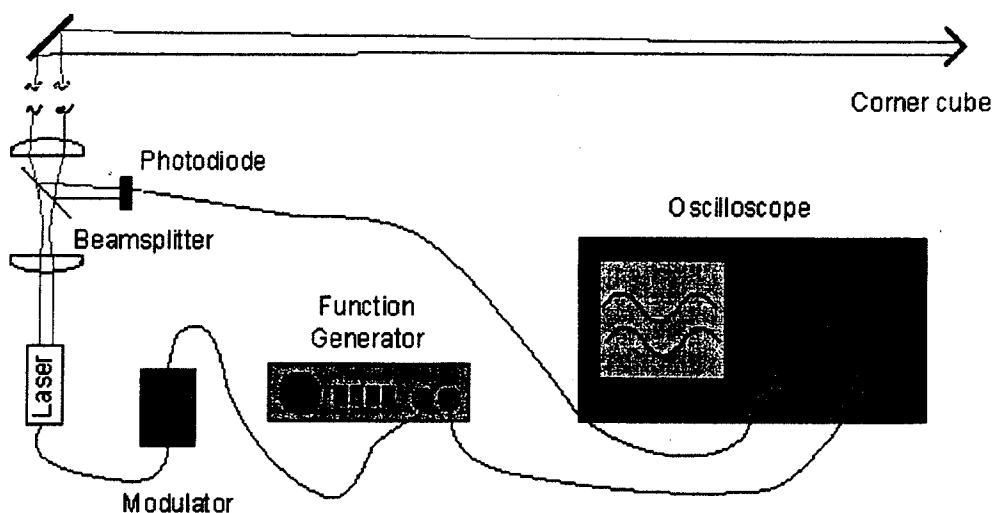
Theory

A conceptually simple way to measure the time taken by light to travel a fixed distance would be to send out a pulse of light to a distant mirror and record the time elapsed between sending the pulse and receiving its reflection. One could use a beamsplitter to send a portion of the pulse directly to the detector and the remainder out to the distant mirror. When this portion of the pulse arrives at the detector it produces a second voltage or current spike. By monitoring the output of the photodetector with an oscilloscope, and timing the interval between the spikes, one can measure the speed of light.

A less expensive alternative is to modulate at reasonably high frequency the output power of a laser beam, again sending a portion directly onto the detector and the remainder out to and back from a distant mirror. Because a periodic wave shifted by any whole number of periods or wavelengths looks exactly the same as the unshifted wave, to know exactly how many periods have elapsed requires some careful thought.

Apparatus

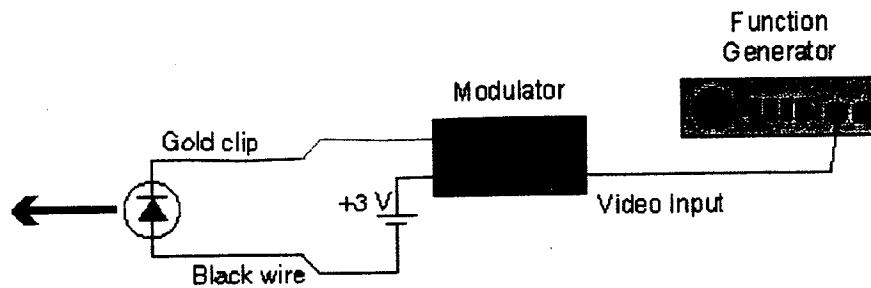
You will use a semiconductor laser modulated by the output of a function generator, which is a device that puts out a periodic voltage with a variable frequency. The setup is shown in the figure below. The beam will pass through a pair of lenses (for reasons to be explained below) and travel some distance to a corner cube reflector. The corner cube sends an incident beam back parallel to itself, so the beam retraces its path, passes through the second lens, reflects off the beam splitter and a portion gets focused onto a photodiode detector. By comparing the signal from the photodiode with that from the function generator driving the laser modulator using the visual representation on the oscilloscope screen, you can determine the time it takes the laser beam to make the round trip.



The laser and detector optics are mounted on a rail which, in turn is mounted on a wooden base. This system will be pre-aligned the first day, but you may need to make fine adjustments to that alignment. Be sure to consult with your instructor on techniques for aligning the optics. *Caution: Small adjustments can have huge (and usually negative) effects!*

Electronics

The laser diode is powered by a dc power supply set at approximately 3 V (*see below*). To modulate the output of the laser, a modulator (also powered by approximately 3 V dc; *see below*) is placed in series with this power supply. By varying the resistance of the modulator, the current through the laser diode is varied, causing the brightness of the diode to change. The circuit diagram for the modulator is shown below. (Note that the polarity of the circuit is important; the diode needs to be reversed biased.)



The laser/modulator can function up to a maximum frequency of 4 MHz, although the depth of modulation will diminish at the highest frequencies. Furthermore, the detector has a maximum frequency it can handle, so be aware that the shape of the modulated signal may vary with frequency.

Cautions

- ***Danger!*** Most laser beams can cause permanent eye damage. ***Never look directly into a laser beam.*** Even though our laser beam is fairly weak, it is important to take care not to expose yourself, your lab partner, or anyone else to a dangerous beam.
- The **laser power supply** should be set initially to **3.30 V**, and the **modulator supply** to **3.40 V**. ***Do not exceed these values!***
- ***Never touch the surfaces of optics.*** The oils on your fingers will significantly degrade the transmission of lenses and the reflection from mirrors. Handle optics carefully by the edges, or by their holders or mounts.

Measuring the Speed of Light: Setup and Initial Studies

1. The modulator has a maximum frequency of 4 MHz, but the amplitude of modulation decreases with frequency, so you will probably have better luck with frequencies closer to 1 MHz.
2. Connect the output of the detector to Channel 1 of the oscilloscope using a BNC cable. Use a tee to send the output of the function generator to both the modulator and Channel 2 of the oscilloscope. Press the trigger button on the scope and select Channel 2 and AC coupling for the trigger source. Adjust the gain setting on Channel 2 and the trigger level until you see a sine wave on the oscilloscope.
3. When you can see a sine wave from the detector on Channel 1, you can begin making your measurement. (You will probably need to start with a setting of about 100 mV/division for Channel 1 and 500 mV/division for Channel 2.) Start with a frequency of 100 kHz on the function generator, and adjust the time base of the oscilloscope and the trigger level to see two or three periods of oscillation.
4. If you don't see a signal from the photodetector, see the troubleshooting section below.

5. Check whether the time base of the oscilloscope and the function generator agree. Using the “Measure” button you can set up a measurement of the frequency of the wave on either channel, or both channels. Make sure you have at least two cycles on the screen to use this feature.
6. Do the signals from the photodetector and the function generator have the nearly the same phase at 100 kHz? Do they basically look the same? If they aren't very close, see the troubleshooting section for tips on adjusting the apparatus.
7. Life would be simple if the phase of the function generator and the phase of the modulator agreed. Life is not simple. To convince yourself of this, place a flat glass plate immediately behind the second lens to send the beam immediately back through the lens, off the beam splitter, and onto the detector. Vary the frequency from 100 kHz to 3 MHz to see how the time lag of the light signal compared to the modulator signal varies with frequency. To correct for this behavior, you should use the reflector at each frequency and each path length you investigate to correct for the electronic phase delay.
8. You can vary the path length by moving the corner cube along the lab bench. You can also increase the path length by inserting one or two plane mirrors between the laser and the corner cube. Use adjustment knobs on the plane mirror mounts to aim the beam onto the corner cube.

Troubleshooting and Measurement Details

Wiring

Make sure that the output of the Video port of the detector is connected to Channel 1 of the scope and that the detector is switched on (the green LED is lit when the detector is on).

Alignment

Make sure that you can see a small, bright red dot of light on the gray square area of the photodiode directly under the Video output. The photodiode can be slid parallel to the rail, and adjustment knobs on the beam splitter can make fine adjustments of the position of the laser spot. These should be the only adjustments you need to make. If you cannot get the spot properly adjusted, please see your instructor. (If you need to make further adjustments, note that each of the optical carriers on the rail has a window with a scribed mark, allowing you to read its position along the rail. Some of these positions are critical; *be sure to record the positions of all carriers before you adjust them!*)

Oscilloscope measurements

For precise and accurate measurements of the time difference between the laser modulator (Channel 2) and the photodiode signal (Channel 1) you need to make sure that the photodiode signal is an undistorted sine wave. If it is distorted, you will need to adjust the laser and/or modulator power supply voltages (see below). You also need to make sure both oscilloscope inputs are AC coupled, with their 0 voltage positions at the same vertical position. To verify this, you can press the Channel 1 button until it is grounded, then look for the trace in the middle of the screen. Rotate the offset knob until the trace is centered. Repeat for Channel 2.

You should measure the time difference between the zero crossings of the sine waves on Channels 1 and 2, both with and without the reflector just behind the second lens. (See item 7 above.) To get the greatest precision in this measurement you will want to adjust both the vertical and horizontal scales on the oscilloscope. Be sure not to move the 0 voltage position of the traces in this process! To measure the time difference, use the cursors in the time mode (Push the "Cursor" button at the top of the oscilloscope and select "Time" for Type of measurement, located just to the right of the oscilloscope screen.) To reduce time jitter on the photodiode signal turn on signal averaging using the "Acquire" button and choose 128 (the maximum) for the averaging number.

Laser

As noted above, the laser power supply should be set initially to 3.30 V, and the modulator supply to 3.40 V. Look at the modulator and photodiode signals and verify that they are symmetrical sine waves. If you see distortions carefully adjust the laser and/or modulator power supplies – downward initially – until the distortion is gone.

Modulator

If the photodiode signal on the oscilloscope is not modulated at the same frequency as the function generator, the modulator potentiometer ("pot") may be adjusted incorrectly. Set the function generator frequency to 1.0 MHz. If that fixes the problem, then you probably had the frequency too high. If not, use a small flat-blade screwdriver to turn the pot counterclockwise until the laser beam dims noticeably. While watching the scope, gradually turn the screw clockwise until you see a signal modulated at the frequency of the function generator.

Created 10/18/00 by Peter N. Saeta;
updated 1/18/02 by Daniel C. Petersen.

6. Miscellaneous Comments

Seek a simple, direct style. Avoid long, complicated sentences in the passive voice. Short, active voice sentences are easier to understand and faster to read. You may use the first person singular if you wish, although it is still rare in formal scientific writing. Use a logical order of presentation and discussion for clarity; avoid reference to details not presented or explained until later in the report.

In writing your technical report, consider your audience to be someone with essentially your background in physics but with no particular knowledge of the experiment you performed.

Appendix A

Technical Report

One of your requirements for Physics 54 is writing a technical report. This report counts the same as two lab write-ups in determining your course grade. You may write the report on any experiment you have completed. The formal requirements are the same as those you saw in Physics 53; the following pages taken from the Physics lab manual should be your guide in this regard. (Also refer to your tech report for Physics 53, including the instructor's comments.) While your report should follow all the guidelines given on the following pages, the emphasis in this report should be on a *careful and thorough analysis of the data*. You will need to consider possible *systematic* errors as well as random uncertainties. This almost certainly means going beyond the analysis you did for your lab write-up. Your goal should be to draw clear, convincing, quantitative conclusions from your experiment.

You should limit your report to 6-10 pages (double-spaced), including figures, any appendices, and references.

A GUIDE TO TECHNICAL REPORT WRITING

The writing of technical reports and journal articles is a part of almost all engineering and scientific work. Because of this you are being instructed in the basics of this skill at an early stage and you will be called upon to write a number of reports during your years at HMC. There are no precise rules which an author can apply to the preparation of a scientific paper as rigorously as a cook follows a recipe, but there are some general principles which will help insure a reasonably smooth and understandable presentation of a body of scientific information. Perhaps the best way to pick up those principles is to read reports and articles appearing in various engineering and scientific journals, such as *The Physical Review*.

One of the most common criticisms of technical reports is that they are not written in a sufficiently brief and concise form. To write succinctly is often difficult. Writing in a rather loose and informal style is much easier, but it simply cannot be tolerated in scientific writing today for some very good reasons. The editor of the *Astrophysical Journal* wrote the following paragraph:

The present accelerated growth of this Journal in common with the other scientific journals, makes it imperative that authors (in their own interest) exercise utmost restraint and economy in the writing of their papers and in the selection and presentation of material in the form of tables, line drawings, and halftones. In spite of the obvious need for such restraint, the Editor regrets that authors continue to write in the relaxed style common a century ago; moreover, the temptation to reproduce large masses of IBM printouts and tracings from automatic recording equipment appears too great for most authors to resist. The Astrophysical Journal will enforce stricter standards in the future with respect to these matters."

The present charge for publication in the leading physics journals is \$70 per page. Thus, it is important that you learn to write your reports in such a way that unnecessary words are eliminated and data is reduced to a minimum. This generally calls for some rewriting.

You should understand that there are also very good reasons for standardizing technical writing. In this day and age, most readers can afford only the time to scan the articles found in journals or the many technical reports used in industry. In order to facilitate that scanning, a certain degree of standardization is very important. For example, if authors present their data in tables of similar form, it becomes relatively easy for the reader to obtain what he wants from those tables without reading all of the text. Similarly, figures should be in a similar form so that they can be studied without referring to the text. It is for this reason that the title on each figure should be written out in words rather than in symbols and that all figures and tables have a caption which tells the reader what is being presented without his having to read the text. Abstracts are also very important to the reader who is scanning rather than reading in detail. You should look at some of the *American Journals of Physics* in order to see how abstracts are written, and all of your technical reports should be preceded by a brief abstract. You should note that abstracts are very specific and give quantitative results. A vague abstract which does not tell what you found out as a result of your work is useless to the reader.

It is important that you understand the distinction between a technical report and a laboratory manual. The latter is designed primarily to give instructions on how an experiment is to be carried out, while the former describes to the reader what the author has done. Though it is sometimes necessary in a technical report to describe the procedures which were followed in carrying out the experiment, such material should be kept to a minimum, and under no circumstances should it instruct the reader as though he were a student in a laboratory.

The following are some suggestions for writing a technical report.

SUMMARY GUIDE FOR A TECHNICAL REPORT

A. Parts of a Technical Report

1. TITLE
2. AUTHOR: author's name
author's institution or company 3 lines
date of submission
3. ABSTRACT: Summary of the principal facts and conclusions of the paper.
Usually less than 100 words.
4. INTRODUCTION: Concise discussion of the subject, scope, and purpose of the experiment.
5. THEORY: Succinct development of the theory related to the experiment.
6. EXPERIMENTAL METHODS: Brief description of experimental apparatus and procedures.
7. RESULTS: Summary of important data and results, using tables and figures (graphs) wherever possible. Include error estimates for all relevant quantities.
8. CONCLUSIONS: Specific conclusions about results. Recommendations if needed. "Graceful termination."
9. REFERENCES: (see below)

B. Mechanics

- a. The paper should be divided into clearly labeled sections, for example: ABSTRACT, INTRODUCTION, THEORY, EXPERIMENTAL METHODS, RESULTS, CONCLUSIONS, REFERENCES.
- b. Type manuscript on bond paper, 8 1/2 x 11 inches.
- c. Double space ALL copy except Abstract.
- d. Number all pages in sequence, beginning with the title page.
- e. Begin Abstract four or five lines below Author information.
- f. Tables and figures:
 - Number tables with Roman numerals, figures with Arabic numerals.
 - Place tables and figures as soon as possible after they are referred to in the text.
 - Give each table and figure a complete title and/or self-descriptive caption.

- g. Number all equations. (Place numbers near right-hand margin.) Each equation should be on a separate line. Use complete sentences and fit all equations into the sentences that introduce them.
- h. Define all symbols used.
- i. Use numbered superscripts to refer to references.

COMMENTS ON "SUMMARY GUIDE FOR A TECHNICAL REPORT"

1. Outline

A detailed outline serves as an excellent writing guide. In composing the outline, make as many subdivisions as possible. It is easier to eliminate or combine existing subheadings than to insert new ones. Be sure the outline reflects the emphasis you wish the paper to have. As you write the paper, the outline may be drastically revised, but it is nevertheless a good starting point.

2. Abstract

As stated earlier, the abstract should be a concise and specific summary of the entire paper. It should be as quantitative as possible and include important results and conclusions. Including all this in less than 100 words takes careful thought (and probably considerable rewriting). You should write the abstract after you have written the rest of the paper, even though it appears first.

3. Introduction

Every scientific paper or technical report should contain at least one or two introductory paragraphs. The first paragraph of the Introduction is particularly critical, since it plays a major role in determining the reader's attitude toward the paper as a whole. It is important enough to warrant considerable time and attention. The following steps are suggested as a means of accomplishing a good Introduction.

- a. Make the precise subject of the paper clear relatively early in the Introduction. You should assume your reader is someone with essentially your background in physics but with no particular knowledge of the experiment you performed. Thus you should include background material only to the extent necessary for the reader to understand your statement of the subject of the paper and to appreciate the scientific reasons for your doing the experiment to be described.
- b. State the purpose of the paper clearly. This statement should orient the reader with respect to the point of view and emphasis of the report and what he should expect to learn from it. A well-done Introduction will also be of great help to you in providing a focus for your writing and in drawing your final conclusions (see below).
- c. Indicate the scope of the paper's coverage of the subject. State somewhere in the introductory paragraphs the limits within which you treat the subject. This definition of scope may include such topics as whether the work described was experimental or theoretical (In this particular case, the work is almost certainly experimental), the exact aspects of the general subject covered by the paper, the ranges of parameters explored, etc.

4. The Main Body

This part of the paper generally includes a brief discussion of the theory, a description of the experimental apparatus and procedure, a presentation of your data and results, and your conclusions. Some suggestions concerning each of these sections follow.

a. Theory

If the major emphasis of your report is the experimental work which you carried out in the laboratory, then the theory may be a reduced version of that given in the laboratory manual. If, on the other hand, the report emphasizes some theoretical aspect of the problem, your section on theory may be an expanded version of the theory given in the laboratory manual. In either case, you should avoid, if possible, simply duplicating the theory given in the laboratory manual. Do not present the details of usual algebraic manipulation, which the reader can easily duplicate. Avoid references to the laboratory manual (find another source!). Note again that the technical report should concentrate on work that you did; a lengthy discussion of the theoretical work of others is not appropriate, in general.

b. Experimental methods

In writing this section you should have in mind a reader who is familiar with typical laboratory apparatus but probably has no intention of repeating your experiment. Therefore, you should describe your experimental apparatus and the procedures you followed only insofar as it is necessary for him to understand how you made your measurements. A careful drawing of the apparatus is often useful here. Keep in mind a person with your background but no knowledge of the specific experiment you are describing.

c. Presentation of data

In most cases this part of your report will be very different from your laboratory notebook. The data should be rearranged in the most concise form possible. This generally means a presentation of important data in simple tables which include average values and final results. Avoid presentation of large amounts of raw data; e.g., simply state that the average of 20 measurements was 1.87 sec with a standard deviation of the mean of .08 seconds. You should strive to make the tables self-explanatory, and results should be included in an obvious way so that a minimum of text is necessary. Graphs and figures can take the place of many words. (Think of the figures in *Scientific American*.) Some form of error analysis should be included with your results, and the uncertainty of the final result clearly stated.

d. Conclusions

Many students find writing this section the most difficult part of the report. This often is the result of insufficient thought given to the organization and purpose of the report before writing began. If the introduction was well thought out, then the conclusions should follow directly from that section. Remember: your conclusions should not be

simply a summary of the experimental results. Rather, they should be convictions arrived at on the basis of evidence previously presented. Make certain that they stem from data presented earlier in the paper and are consistent with your introductory paragraph, in that they fulfill any promise you made to the reader at the beginning as to what your paper would prove. They should not include findings and deductions for which no previous evidence was offered. This section will generally expand on the analysis made in the lab notebook. Avoid vague generalities; be quantitative, precise and specific. You may want to include suggestions for future work. If possible, this section of your paper should end with what is generally called a "graceful termination."

5. References and Appendices

At the end of your report there should definitely be a set of references. In the main body of your report a number should appear whenever reference is made to some outside source of writing. At the end of the report the references should then be listed with corresponding numbers. To give a list of references at the end of a report without any specific numbered reference within the text is incorrect. Such a listing is more properly called a bibliography; in most short technical report writing bibliographies are not given. Thus, it is suggested you get in the habit of making specific references to outside sources and only occasionally give a bibliography, when a paper is a very comprehensive one. Give references to generally accessible works, e.g., textbooks and well-known journals. Do not give references to items of limited circulation such as an HMC laboratory handout. Find another more generally accessible substitute.

The following examples of references come from the AIP (American Institute of Physics) Style Manual (American Institute of Physics, New York, 1979).

Journal article citations

Same author, two different journals

- ¹Gale Young and R.E. Funderlic, *J. Appl. Phys.* **44**, 5151 (1973).
²T.L. Gilbert, *Phys. Rev. B* **12**, 2111 (1975); *J. Chem. Phys.* **60**, 3835 (1974).

Same authors, two references to same journal (one an erratum); different author, same journal

- ³T. Nenner, H. Tien, and J.B. Fenn, *J. Chem. Phys.* **63**, 5439 (1975); **64**, 3902(E) (1976); Harold F. Winters, *ibid.* **64**, 3495 (1976).

Article title included

- ⁴R. Plomp, "Rate of decay of auditory sensation," *J. Acoust. Soc. Am.* **36**, 277-282 (1964).

Issue number included

- ⁵Marc D. Levenson, *Phys. Today* **30** (5), 44-49 (1977).

Year in place of volume number

- ⁶H.W. Taylor, *J. Chem. Soc.* **1966**, 411.

Translation-journal article

- ⁷V.I. Kozub, *Fiz. Tekh. Poluprovodn.* **9**, 2284 (1975) [*Sov. Phys. Semicond.* **9**, 1479 (1976)].

Book references

- ⁸L.S. Birks, *Electron Probe Microanalysis*, 2nd ed. (Wiley, New York, 1971), p. 40.

- ⁹D.K. Edwards, in *Proceedings of the 1972 Heat Transfer and Fluid Mechanics Institute*, edited by Raymond B. Landis and Gary J. Hordemann (Stanford University, Stanford, Calif., 1972), pp. 71-72.

Different authors, same book

- ¹⁰Robert G. Fuller, in *Point Defects in Solids*, edited by James H. Crawford, Jr., and Lawrence M. Slifkin (Plenum, New York, 1972), Vol. 1, Chap. 2, pp. 103-150; M.N. Kabler, *ibid.*, Vol. 1, Chap. 6, pp. 327-380.

References to unpublished work

- ¹¹J. Moskowitz, presented at the Midwest Conference on Theoretical Physics, Indiana University, Bloomington, Ind., 1966 (unpublished).

- ¹²R.C. Mikkelsen (private communication).

- ¹³R.T. Swan and C.M. Pitman, Saclay Report No. CEA-R 3147, 1957.

- ¹⁴James B. Danda, Ph.D. thesis, Harvard University, 1965.

Reference to patent

- ¹⁵W.J. Thompson and D.R. Albert, U.S. Patent No. 7 430 020 (3 March 1975).

Reference to film

- ¹⁶*Technology: Catastrophe or Commitment?*, film produced by Hobel-Leiterman Productions, Toronto (distributed by Document Associates, Inc., 880 Third Ave., New York, N.Y. 10022; released 1974), 16 mm, color, 24 min.

Reference to computer program

- ¹⁷Norman R. Briggs, computer code *CRUX* (Bell Laboratories, Murray Hill, N.J., 1972).

Appendices are commonly found in reports, but they should not be overdone. That is, you should avoid the use of appendices unless you feel it is very necessary to present some additional material which does not fit into the main body of your report.

6. Miscellaneous Comments

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