Feb. 2004

Cathode Rays and Cyclotron Motion Phy 344

Introduction:

The term "cathode" was selected by Michael Faraday to refer to the configuration of his electrochemistry experiments. Two electrodes were inserted into a solution, typically consisting of water and a little salt. The "cathode" was connected to the negative terminal of a battery, the "anode" to the positive terminal. Hydrogen gas was liberated at the cathode, and oxygen at the anode.

Remarkable things also occurred when the two electrodes were inserted into vacuum tubes: something unknown, a "cathode ray," emerged from the cathode. The contemporary expression "CRT" used to describe television sets and computer monitors stands for "cathode ray tube;" this expression is a relic of the time when it was not yet established that cathode rays were the charged particles now known as electrons.

In this experiment you may try to imagine that you are attempting to establish that cathode rays are negatively charged particles. The path of the cathode rays will be made visible in two ways. First, when the rays hit a *phosphorescent* screen, the screen glows. The same principle underlies television sets, oscilloscopies, and computer monitors. Second, some of the rays collide with gas atoms in the vacuum tube. These atoms also glow, or *luminesce*. You can affect the cathode rays in several ways: by changing the voltage between the cathode and anode, by changing the temperature of the cathode, and by applying a magnetic field to the tube. If cathode rays are moving, charged particles, the magnetic field should cause them to follow a circular path, or "cyclotron" orbit.

Objectives

- Learn to wire and operate a vacuum diode.
- Measure the current-voltage relationship of a vacuum diode for two filament temperatures; achieve a qualitative understanding of these relationships.
- Learn to use Helmholtz coils for generating small magnetic fields.
- Understand the principles of cyclotron motion.

- Observe cyclotron motion of cathode rays, and compare these observations with theory. Obtain an experimental estimate of the charge to mass ratio for the electron.

Suggested Reading:

- Theodore Korneff, *Introduction to Electronics* (Academic, New York, 1973), pp. 111-117. This book contains an introduction to vacuum diodes, of which the cyclotron motion tube is an example.

Suggested Apparatus:

1. Welch Scientific Company cyclotron motion apparatus. The apparatus consists of a large vacuum tube mounted between two large coils of wire; the tube and coils can be tilted. The specifications for the tube and the coils are filed under "Welch;" the manufacturer's manual for the tube is not available.

   (i) Vacuum tube. The cathode in the tube is actually a "filament" of wire which is heated quite hot by electric current. The anode is a cylinder surrounding the cathode with a slot. The tube also has a long "marker bar" for determining the diameter of the cyclotron orbits.

   (ii) Helmholtz coils. The two coils are known as "Helmholtz" coils, and are used to generate a fairly uniform magnetic field at the vacuum tube. Each coil has 72 turns.

2. High-voltage DC power supply for the vacuum tube. No manual is available.

3. DC power supply for the filament of the vacuum tube. Use the Lambda LL-902-OV. Make sure you connect this supply through the $\sim 23\Omega$ resistor chain, otherwise you are likely to burn out the tube.

4. High current supply for the Helmholtz coils. Use LAMBDA model LLS6018.

5. Multimeter. Keithley model 175; manual filed under Keithley.

6. Compass. Used to determine the direction of the Earth's magnetic field; the instructions are printed on the compass.

Safety Considerations: The DC power supply can deliver a high voltage. Adjust it carefully. Apply high voltage only to the anode in the tube; the cathode should be kept as close to ground potential as possible. Please connect the center jack of the DC filament supply to ground; this instruction is very important to avoiding electric shock from the rheostat and other parts of the cathode circuit.

Avoiding Damage: The filament is very sensitive. Do not exceed 0.27 Amperes of filament current.

Instructions - Theory of Cyclotron Motion

1. Determine the motion of a particle with charge e, mass m, and initial speed v in a magnetic field of strength B. Assume that the path is confined to a plane perpendicular to the field; you should be able to show that the motion is a circle with radius
$$r = \frac{mv}{eB} \quad . \tag{1}$$
This equation uses standard SI units (meters, kilograms, Coulombs, Tesla, and Volts).

2. In the cyclotron motion apparatus, the speed of the particle is determined by the anode-cathode voltage V. Charged particles are emitted by the heated cathode, accelerated by the electric field between the anode and cathode, and then fly into a vacuum space with only very small electric fields. Derive the following expression relating the cyclotron radius r to the anode-cathode voltage V:
$$r = \frac{\sqrt{2Vm/e}}{B} \quad . \tag{2}$$

Instructions - Field of Helmholtz Coils

1. The magnetic field in this experiment is generated by two thin, parallel coils arranged concentric to the same axis. Calculate the magnetic field of such coils at the midpoint on the axis between them; you can probably look up the necessary derivation in your elementary physics textbook. Assume that each coil has $N = 72$ turns, radius R that you can measure, and current I (that you will apply to the coils). The distance between Helmholtz coils is R, the same as the radius of the coils.

2. However, the magnetic field due to the Earth is not necessarily small compared to the field you are producing and must be added in. Furthermore being a good scientist you are suspicious of the calculation that uses several assumptions in the derivation and wish to measure the field. You can do this with a Hall probe, the F. W. Bell model BH-850. (You can read about how the Hall probe works in the file.) You need to supply a 200 ma control current to the probe. You do this by using the red lead as + and the black lead as -. (You can use the LAMBDA power supply for this.) You then read the Hall voltage across the blue (+) and yellow (-) leads. The magnetic field is proportional to the Hall voltage. The calibration constant is 18 mV/G. That is, if you control the current at 200 ma, you will read 18 mV for each Gauss of magnetic field. arrow drawn on the probe must be parallel to the direction of the field you are trying to measure. If the probe is at an angle to the field you will be measuring only the component of the field along the arrow. Therefore, you should move the probe around to get the maximum field.)

   Unfortunately this Hall probe is only useful for measuring a few Gauss. So what you need to do is measure the magnetic field with the Hall probe as a function current, starting at zero current, and see where the Hall probe output saturates, or becomes non-linear. After you figure out for what values of the magnetic field you are getting a reasonable reading, subtract out the value of the earth's field (the zero current point) and compare with your calculation of the field. After you obtain agreement you can then use the calculation plus the earth's field to provide an accurate value of the magnetic field the electrons see.

Instructions - Operation of the Vacuum Diode

1. Make a neat diagram of the components in the vacuum tube. Your drawing should show the structure of the assembly containing the filament/cathode, the anode, and the marker bars inside the tube.

2. Design wiring for this tube to furnish a variable filament heating current using the Lambda DC supply and a variable anode voltage using the Harrison High Voltage DC power supply. *It is imperative that you keep the* $\sim 20\Omega$ *resistance chain in the circuit to prevent damage to the filament.* Provide for a measurement of the current between the anode and cathode. Make a block diagram showing your design. Wire your design; ask a staff member to check your wiring before you turn anything on.

3. Measure the dependence of the current i between the anode and cathode as a function of the voltage V between them for at least two filament currents, below the maximum allowed. Graph these measurements on a single sheet of graph paper so that the effects of changing the filament heating current are readily apparent. Don't forget to explore voltages of *both* polarities.

Instructions - Cyclotron Motion Observations

- Decide how to deal with the Earth's magnetic field, which will affect your measurements. Note that the apparatus can be tilted and rotated if necessary. Describe your plan in your notebook; align the apparatus if required.

- Turn on the filament heating current. Make a qualitative study of the orbits observed in the tube in a darkened room as the anode-cathode voltage V is varied and as the magnetic field is varied. Summarize your observations in your notebook.

- Pick a convenient current for the Helmholtz coils. Record the anode-cathode voltage required for the cathode ray beam to hit each of the five marker posts in the tube. Repeat these measurements for at least two other Helmholtz coil currents selected to be as large and as small as practicable.

- Graph your measurements of radius r vs. voltage V to test whether they agree with equation (2) above; in particular design this graph so that, if the theory is correct, a straight line will result. Carefully analyze the slopes to estimate the ratio e/m of the charge and the mass of the cathode ray.

- Compare your estimates to the ratio of charge to mass e/m for the electron quoted in textbooks; the comparison should include an estimate of the reproducibility of your e/m measurement.

Memoranda: Be prepared to orally discuss the following points; there is no need to prepare written responses.

- What accounts for the shape of the current-voltage curve of the tube?

- Does the AC voltage applied to the filament affect the voltage between the anode and cathode?

- Is it satisfactory to use the expression for the magnetic field at the center of a Helmholtz coil to describe the magnetic field over the entire cyclotron orbit?

- Can you estimate the Earth's magnetic field from your data? Does your value agree with textbook estimates?
- Were you able to determine if the cathode rays were negatively or positively charged?