Measurements and Software

Software needs to convert each potentiometer voltage to an angle, acquire the number of pulses received for each position during some fixed counting period, store the data, and plot the results.

Calibration should be achieved at the beginning of each run by setting the detector at the end points of the range. Background counts need to be acquired and used to adjust the data. The maximum allowable count rate will be determined by the G–M tube and by the software. This last consideration is discussed further in the text of Experiment 6, in the section entitled Computer-Assisted Counting and Data Analysis.

Atomic and Molecular Physics

11. FRANCK–HERTZ EXPERIMENT: ELECTRON SPECTROSCOPY

Historical Note

The 1925 Nobel prize in Physics was awarded jointly to James Franck, Germany and Gustav Hertz, Germany

For their discovery of the laws governing the impact of an electron upon an atom

Franck and Hertz performed the experiment in 1914, 12 years before the development of quantum mechanics, and it provided striking evidence that atomic energy states are quantized.

APPARATUS [Optional Apparatus in brackets]

Franck–Hertz tube
Electric oven
Variac
Thermocouple and temperature potentiometer
Electrometer
Circuit to provide dc voltages for the Franck–Hertz tube, see Figure 11.5
6.3-V ac filament supply
Oscilloscope [with an available sawtooth voltage]

[Oscilloscope camera]
[Microcomputer, ADC/DAC card, conditioning circuits (see Figures 11.5, 11.8, and 11.9)]
[*xt* chart recorder]

OBJECTIVES

To verify the quantization of atomic electron energy states of mercury atoms by observing the maxima and minima of an electron current passing through a gas of mercury atoms.

To understand how ordinary and metastable atomic electron energy states of mercury affect the transmission of electrons.

To understand how temperature affects the number density of mercury atoms, the mean free path of a transmission electron, and the kinetic energy of a transmission electron.

KEY CONCEPTS

Elastic and inelastic scattering
LS coupling
Ordinary states
Metastable states
Mean free path
Contact potential difference
Forbidden transitions
Allowed transitions

REFERENCES

1. R. Eisberg and R. Resnick, *Quantum Physics of Atoms, Molecules, Solids, Nuclei, and Particles*, 2d ed., Wiley, New York, 1985. Contact potential is discussed on pages 407–408 and the Franck–Hertz experiment is briefly discussed on pages 107–110.
2. D. Halliday and R. Resnick, *Physics*, Part I, 3d ed., Wiley, New York, 1978. Mean free path is discussed on pages 522–524.
3. K. Rossberg, *A First Course in Analytical Mechanics*, Wiley, New York, 1983. Collision of two particles is discussed on pages 157–160.
4. L. Loeb, *Atomic Structure*, Wiley, New York, 1938. An older book which you may find in the library. A good discussion of the Franck–Hertz experiment appears on pages 249–254. The energy levels of mercury are discussed on pages 256–264.
5. E. Leybold, Manufacturer's description of the Franck–Hertz tube. This is a discussion of the Franck–Hertz tube, which should be available from your instructor.
6. R. Eisberg, *Fundamentals of Modern Physics*, Wiley, New York, 1961. LS coupling is discussed on pages 428–441.

INTRODUCTION

The Franck–Hertz experiment, first performed in 1914, verifies that the atomic electron energy states are quantized by observing maxima and minima in transmission of electrons through mercury vapor. The variation in electron current is caused by inelastic electron scattering that excites the atomic electrons of mercury. The Franck–Hertz tube, which contains a drop of mercury, is shown in Figure 11.1 along with electrical connections. The tube requires the following operating voltages

Filament, f: 6.3 V ac. Operation at a lower voltage will increase the lifetime of the tube.

Space-charge grid voltage across grid G_1 and cathode k: $V_s = 2.7$ V dc. This voltage determines the space charge about the cathode and, thus, the emission current. See the

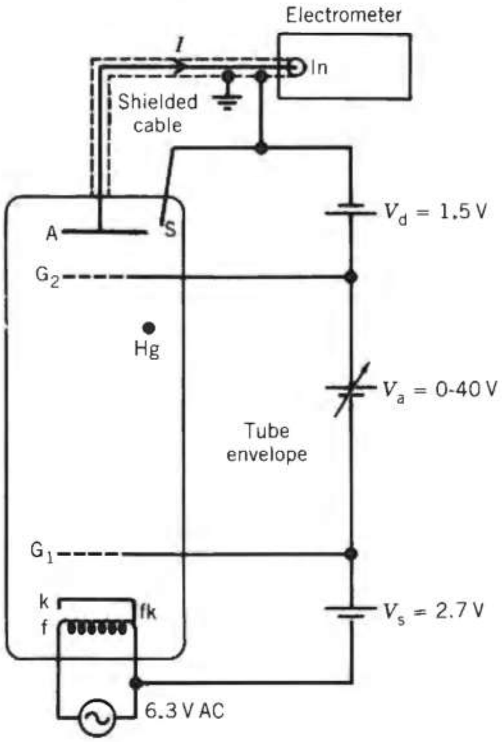

FIGURE 11.1 Schematic diagram of the Franck–Hertz tube with electrical connections.

discussion of space charge and emission current in Experiment 7, Electron Physics. Some tubes do not have grid G_1. For such tubes the voltage V_s is omitted and the negative terminal of V_a connects directly to fk.

Accelerating voltage across grid G_2 and cathode k: $V_a = 0\text{–}40$ V dc.

Decelerating voltage across anode A and grid G_2: $V_d = 1.5$ V dc. Only those electrons that arrive at G_2 with an energy greater than eV_d will reach the anode A.

The electrodes of the Franck–Hertz tube are coaxial, cylindrical electrodes as shown in Figure 11.2. The tubes that do not have grid G_1 have noncylindrical electrodes.

Energy Levels of Mercury

A mercury atom has 80 electrons. For an atom in the ground state the K, L, M, and N shells of mercury are filled and the O and P shells have the following electrons:

0 shell: $5s^2$, $5p^6$, $5d^{10}$

P shell: $6s^2$

Energy levels of mercury, which are relevant to this experiment, are shown in Figure 11.3. (See reference 4 for a discussion of the energy levels of mercury.) The energy levels are labeled with two notations:

$n\ell$, where n is the principal quantum number and ℓ is the orbital angular momentum quantum number, designated by $s(\ell = 0)$ and $p(\ell = 1)$.

${}^{2S+1}L_J$, where S, L, and J are the total spin quantum number, total orbital angular momentum quantum number, and total angular momentum quantum number (see reference 6).

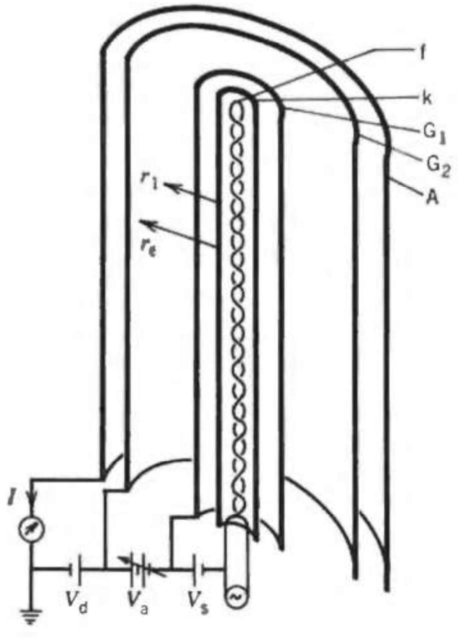

FIGURE 11.2 The electrodes of the Franck–Hertz are coaxial, cylindrical electrodes.

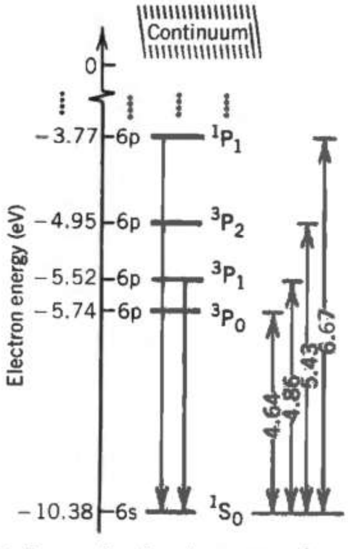

FIGURE 11.3 Energy levels of mercury that are relevant to this experiment. Energy level separation in electron volts is indicated on the right.

The $^1P_1$ and $^3P_1$ are ordinary states, having lifetimes of about 10^{-8} s before decaying to the $^1S_0$ ground state by photon emission. The $^3P_2$ and $^3P_0$ are metastable states, having lifetimes of about 10^{-3} s or 10^5 times as long as an ordinary state. (See the discussion of metastable states in the "Introduction to Laser Physics.") Hence, the probability per second of an electron making a transition from either the $^3P_2$ or $^3P_0$ state to the $^1S_0$ ground state by photon emission is 10^5 times smaller than the transition from either the $^3P_1$ or $^1P_1$ to $^1S_0$. Thus, the transitions from $^3P_2$ and $^3P_0$ to $^1S_0$ are *forbidden* transitions, while the transitions from $^1P_1$ and $^3P_1$ to $^1S_0$ are *allowed* transitions. The allowed transitions for photon emission are indicated by the two arrows on the left in Figure 11.3, and the four arrows on the right indicate energy spacing in units of electron volts.

Direct excitation of ${}^3P_0$, ${}^3P_1$, ${}^3P_2$, and ${}^1P_1$ from ${}^1S_0$ by electron impact is essentially equally probable.

Atomic Excitation by Inelastic Electron Scattering

An electron traveling from the cathode k toward the anode A has a mean free path $\bar{\ell}$ (see reference 2) given by

$$\bar{\ell} = \frac{1}{\sqrt{2}\pi n R_0^2} \qquad \text{(m)} \tag{1}$$

where $R_0 \simeq 1.5 \times 10^{-10}$ m is the radius of a mercury atom and n is the number of atoms per unit volume. At the end of one mean free path the electron has gained a kinetic energy K from the electric field E:

$$K = eE\bar{\ell} \qquad \text{(J)} \tag{2}$$

where e is the electron charge and E is the electric field established by the accelerating voltage V_a. If $\bar{\ell}$ is long, then K will be large.

The number density n is very sensitive to the tube temperature; therefore ℓ and, hence, K are very temperature sensitive.

EXERCISE 1

What is the mean free path $\bar{\ell}$ of an electron in a Franck–Hertz tube heated to 373 K? 423 K? 473 K? Assume the gas of mercury atoms behaves as an ideal gas. A table of vapor pressure of mercury and temperature may be found in the *CRC Handbook of Chemistry and Physics*.

When an electron of kinetic energy K approaches a mercury atom with $K < 4.6$ eV, the energy difference between the first excited state and the ground state, then the collision is elastic. In an elastic collision the electron loses some kinetic energy determined by the laws of conservation of momentum and kinetic energy.

EXERCISE 2

The loss of kinetic energy by an electron when it collides elastically with a mercury atom is greatest when the collision is head-on. For an elastic head-on collision with the mercury atom, assumed initially at rest, show that the change in electron energy is given by

$$\Delta K = \frac{4mM}{(m+M)^2} K_0 \qquad \text{(J)} \tag{3}$$

where m and M are the masses of an electron and a mercury atom and K_0 is the initial electron energy. (See reference 3 for a discussion of a head-on, two-particle collision.) What is the fractional loss of kinetic energy by the electron for such a collision?

From your answer to Exercise 2 it should be clear that the loss of electron energy due to a single elastic collision is negligibly small. The probability of an inelastic collision occurring is large when the electron's energy equals the energy difference between an excited state and the ground state of the mercury atom, that is, 4.6, 4.9, 5.4, and 6.7 eV (see Figure 11.3). At some radial distance $r_1 \pm \Delta r$ from the cylindrical cathode k, the kinetic energy K of the electron will equal 4.6 eV and the first inelastic collision occurs. An arbitrary r_1 is shown in Figure 11.2. The inelastic collisions occurring in the cylindrical shell of radius $r_1 \pm \Delta r$ populates the $^3P_0$ metastable state of the mercury atoms in the shell. The electrons that later enter the shell will collide elastically with the mercury atoms that are in the $^3P_0$ state; hence, these electrons pass through the shell with negligible energy loss. At some larger radius $r_\varepsilon \pm \Delta r$ (shown in Figure 11.2) these same electrons will have a kinetic energy of $\varepsilon = 4.9$ eV and they collide inelastically with mercury atoms in the ground state. The $^3P_1$ state decays to the $^1S_0$ state after about 10^{-8} s by photon emission, and then the atom is ready for another inelastic collision; that is, the atoms in this shell continuously convert electron kinetic energy to radiant energy. If the accelerating voltage V_a is high enough, this process may be repeated in cylindrical shells of radii $r_{2\varepsilon} \pm \Delta r$, $r_{3\varepsilon} \pm \Delta r, \ldots$. Note that r_ε, $r_{2\varepsilon}$, and so on are the distances of travel required for the electron to gain a certain energy.

What effect do these inelastic collisions have on the current measured by the electrometer in Figure 11.1? The decelerating voltage V_d is 1.5 V and as V_a is increased from 0 V a current is first observed when V_a exceeds 1.5 V and the observed current will increase as V_a increases until $V_a = 4.9$ V. When $V_a = 4.9$ V the electrons lose energy from inelastic collisions; hence, they no longer have enough energy to overcome the 1.5-V decelerating voltage and the observed current decreases. (With $V_a = 4.9$ V, r_ε is approximately the distance from the cathode k to the grid G_2.) As V_a is increased from 4.9 V the current will again increase until $V_a = 9.8$ V, which corresponds to a second cylindrical shell a distance of $r_{2\varepsilon} \pm \Delta r$ from the cathode where inelastic collisions which populate the $^3P_1$ state occur. Thus, when $V_a = n \times 4.9$ V, $n = 1, 2, 3, \ldots$, there is a decrease in current. A curve of expected current I versus accelerating voltage V_a is sketched in Figure 11.4. Each peak represents the onset of inelastic collisions that populate the $^3P_1$ state. The first peak does not occur at 4.9 V because of the contact potential difference between cathode and anode. Contact potential difference is discussed in reference 1.

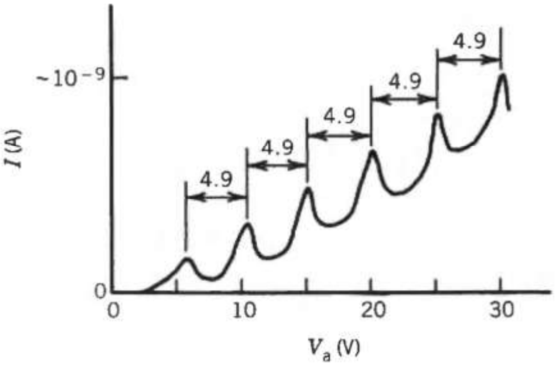

FIGURE 11.4 Electrometer current as a function of the accelerating voltage V_a.

EXERCISE 3

Determine the accelerating voltage V_a as a function of the radius r measured from the cathode. Then show that the ratio of the radii of the first two cylindrical shells is given by

$$\frac{r_{2\varepsilon}}{r_\varepsilon} = e^{2\pi\epsilon_0 4.9/\lambda}$$

where $\epsilon_0 = 8.85 \times 10^{-12}$ F/m, λ is the magnitude of the charge per unit axial length of the cathode, and the numerical value 4.9 has units of volts. Assume that there is no space charge surrounding the cathode and that the length of the cylindrical electrodes is much greater than the diameter; that is, assume an infinite length.

EXPERIMENT

Read reference 5, the manufacturer's description of the Franck–Hertz tube. Note the precautions specified in this description.

Circuit to Provide Dc Voltages for the Franck–Hertz Tube

The electrical circuit to provide the dc voltages for the Franck–Hertz tube is shown in Figure 11.5. The point labeled S in 11.5 connects to the shield, G_1 connects to grid 1, G_2 connects to grid 2, and fk connects to the filament–cathode. Compare these connections with the equivalent connections shown in Figure 11.1. In Figure 11.5 the 1.5-V D cell provides the decelerating voltage V_d, the accelerating voltage V_a is the voltage between the emitter and collector of the SK 3025 transistor, $V_a = V_{G_2} - V_{G_1}$, and the 2.7-V Zener diode provides the space-charge voltage V_s. If a tube does not have grid G_1 then the 2.7-V Zener and the lead labeled G_1 are omitted. Note that the ac filament supply for the tube is not included in Figure 11.5.

In terms of the accelerating voltage the desired output of the circuit is $V_a = 0$ to $+40$ V. How does the circuit provide this voltage? Well, the collector voltage, and, hence, the accelerating voltage, is controlled by the collector current; the collector current is controlled by the bias voltage of the emitter–base junction; and the bias voltage is controlled by the output of op-amp 2. The output of op-amp 2 is given by

$$V_{\text{out},2} = -\frac{R_2}{R_1} V_{\text{out},1} = +\frac{R_2}{R_1} V_{\text{in}} \qquad (\text{V}) \tag{4}$$

where the output of op-amp 1 is the negative of its input, V_{in}. Op-amps are discussed in reference 5, Experiment 6.

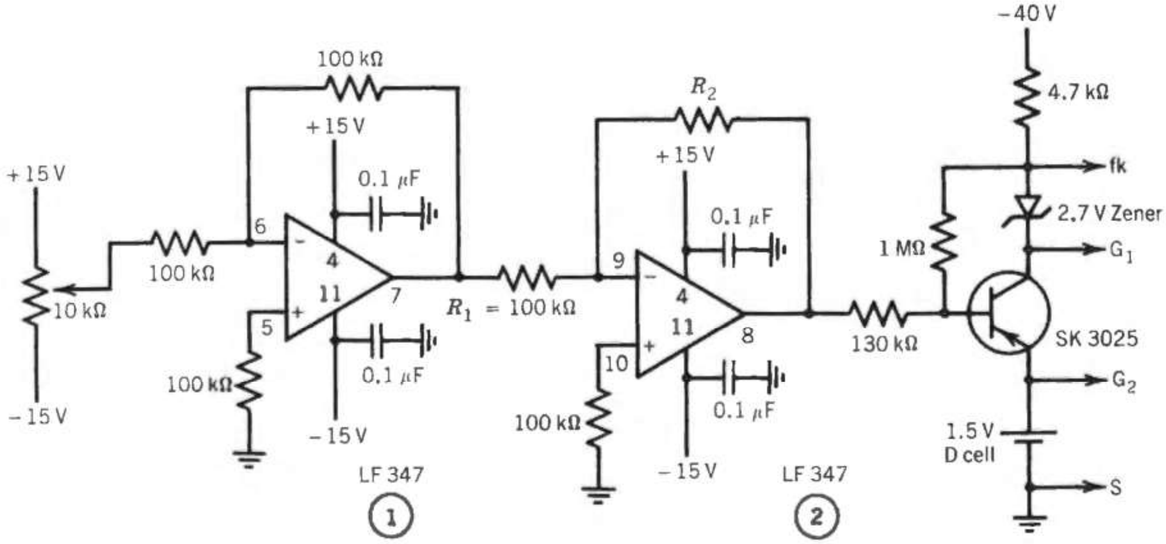

FIGURE 11.5 Circuit to provide the dc voltages for the Franck–Hertz tube. This circuit is also used in computer-assisted experimentation with the replacement of the dc voltage input with the analog output of the DAC, where the analog range of the ADC/DAC card is $-K$ to $+K$ volts.

An op-amp 2 output of -6.5 V provides a "forward" bias to the emitter–base junction and the resulting collector current is large, creating a voltage drop across the 4.7-kΩ resistor of about 39 V. In this case the accelerating V_a is approximately zero. An op-amp 2 output of $+6.5$ V provides a "reverse" bias to the emitter–base junction and the collector current is then zero; hence, the collector voltage is -40 V and V_a is $+41$ V. As the output of op-amp 2 ranges from -6.5 to $+6.5$ V the accelerating voltage ranges from 0 to 41 V.

The input to op-amp 1 is the voltage on the "slider" of the 10-kΩ potentiometer. We (arbitrarily) use an input of -5 to $+5$ V, and then select R_2 such that op-amp 2 has the desired output. (The $+15$ and -15 V shown connected to the 10-kΩ potentiometer may be obtained from the op-amp power supplies.)

EXERCISE 4

For an input V_{in} ranging from -5 to $+5$ V what value of the resistance R_2 is required?

A top view of the pin assignment of the LF 347 op-amp is shown in Figure 11.6. Note that the package is actually four op-amps. Each op-amp is a JFET input op-amp with an input impedance of 10^{12} Ω. JFET op-amps are discussed in reference 5, Experiment 6.

It is suggested that you bench test the circuit before connecting it to the Franck–Hertz tube. To do so, measure the voltages at the points labeled G_2, G_1, and fk as the input voltage to op-amp 1 is varied from -5 to $+5$ V.

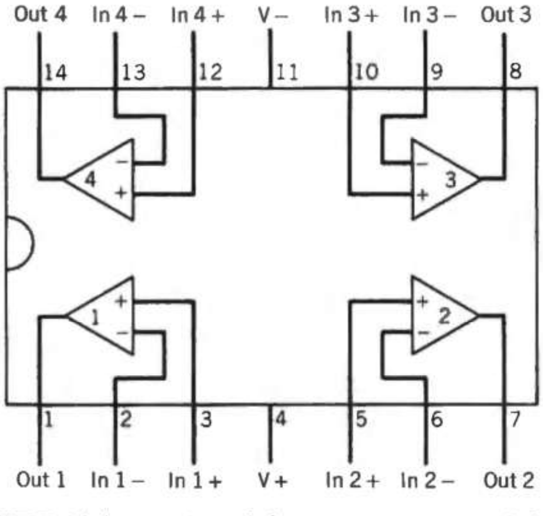

FIGURE 11.6 Top view of the pin assignments of the LF 347 op-amp. The package is actually 4 op-amps.

Electrometer

Electrometers are extremely sensitive electronic instruments designed to measure both (+) and (−) currents and voltages. A function switch permits the selection of current or voltage mode. A range selector switch allows voltage measurements from about 1 μV to 1 V and current measurements from about 1 pA to 1 mA. The output of the electrometer ranges from 0 to plus or minus a few volts for an input ranging from 0 to full scale.

The output current of the Franck–Hertz tube ranges from 0 to about -10^{-9} A as the accelerating voltage varies from 0 to $+30$ V (voltage of G_2 relative to fk). Two instruments for measuring the output of the Franck–Hertz tube are briefly described below.

The manufacturer lists the specifications of the Hewlett-Packard Model 425A dc microvolt ammeter as the following:

Voltmeter input impedance	$10^6\ \Omega \pm 3\%$
Voltage range	10^{-6} V full scale to 1 V full scale
Ammeter range	10^{-12} A full scale to 3×10^{-3} A full scale
Output	0 to ±1 V for 0 to full-scale input; output polarity is the same as the input
Ac rejection (at amplifier output)	At least 1 db at 1.0 Hz, 50 db at 50 Hz

The specifications of the Keithley Model 610C electrometer, as listed by the manufacturer, are:

Voltmeter input impedance	$10^{14}\ \Omega$
Voltage range	10^{-3} V full scale to 10^2 V full scale
Ammeter range	10^{-14} A full scale to 0.3 A full scale
Output	0 to ±3 V for 0 to full-scale input; output polarity is opposite input polarity
Frequency response	Dc to 100 Hz

The ac rejection at the amplifier output of the Hewlett-Packard instrument implies that it is a dc instrument, and the frequency response of the Keithley instrument indicates it is a dc or quasi-dc measuring device.

A circuit to bench test the electrometer is shown in Figure 11.7. Select a value of R appropriate for an electrometer input of 10^{-3} V full scale, say, then measure the electrometer output as a function of the input. Reverse the polarity of the 1.5-V D cell and repeat the measurements. To test a different input range of the electrometer change R to a value appropriate for that range.

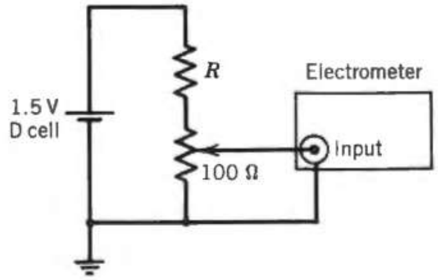

FIGURE 11.7 Circuit to bench test the electrometer.

Connecting the Circuit to the Franck–Hertz Tube

Turn off all voltages and then connect the circuit and filament power supply to the Franck–Hertz tube. NEVER APPLY VOLTAGES TO THE TUBE UNLESS IT IS IN THE OVEN AT THE DESIRED TEMPERATURE. To do otherwise could burn out the tube, and it is expensive. After connecting the circuits to the tube, then:

1. Attach the thermocouple to the tube (approximately centered on the anode), place the metal shield around the tube and connect it to ground (this will reduce ac pickup), and then insert the tube into the oven as deeply as possible.

2. Plug the oven into the variac and experiment with the oven temperature as a function of voltage. You want to determine the variac setting(s) required to bring the tube–oven system to the desired temperature as quickly as possible. The voltages to the tube may be applied after a stable operating temperature is reached.

With the anode connected to the electrometer as shown in Figure 11.1 vary the input voltage to op-amp 1 from -5 to $+5$ V, recording appropriate currents and voltages in your notebook. Also measure the temperature periodically and adjust the oven voltage as required to maintain a reasonably constant temperature.

Analyze the data, interpreting it in terms of the theory discussed in the Introduction.

EXERCISE 5

The cathode at temperature T emits electrons with a distribution of speeds. The average kinetic energy $\bar{K}$ of the electrons is

$$\bar{K} = 2kT \qquad \text{(J)}$$

where k is the Boltzmann constant and T is the absolute temperature. Assuming that T is 2500 K, what effect will $\bar{K}$ have on your measured excitation potentials? What effect will the distribution of speeds of the electrons have on the sharpness of the peaks?

EXERCISE 6

What effect would contact potential have on peak spacing? What peak positions would be affected by contact potential?

Optional Experimental Method

The experimental method described below requires two additional pieces of equipment, namely, an oscilloscope with an available sawtooth voltage and an *xt* recorder. If this equipment is available you may want to omit the previous measurements and carry out the experiment below.

A problem with the preceding experiment is the temperature variation that occurs while recording data. If the data could be recorded in an appropriately short time interval then the temperature variation would be small. We now discuss such a method of recording the data.

Consider the circuit in Figure 11.8. The 10-kΩ potentiometer is connected across the horizontal sweep voltage of the oscilloscope, the *scope sawtooth*. The slider on the potentiometer may be adjusted such that the slider voltage is a 10-V sawtooth, that is, the input to op-amp 1 is a sawtooth ranging from 0 to $+10$ V. The desired output of op-amp 2 is -6.5 to $+6.5$ V. How do we obtain this output? Well, the output of op-amp 2 is

$$V_{\text{out},2} = -\frac{R_2}{R_1} V_{\text{out},1} + \frac{R_1 + R_2}{R_1} V_{\text{off}} \qquad \text{(V)} \tag{5}$$

where V_{off} is the adjustable offset voltage and $V_{\text{out},1}$ is the output of op-amp 1. Op-amp 1 is configured to have a gain of -1; hence, its output will be a sawtooth voltage ranging from 0 to -10 V.

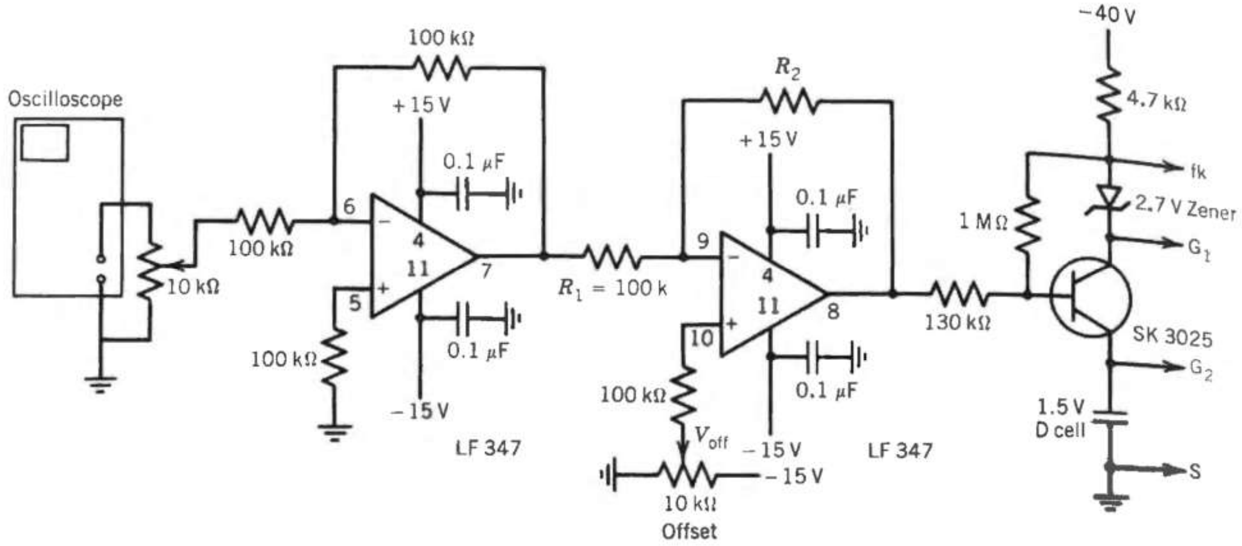

FIGURE 11.8 Circuit with a 0 to +10 V sawtooth input that provides the dc voltages for the Franck–Hertz tube. This circuit is also used in computer-assisted experimentation with the replacement of the sawtooth input with the analog output of the DAC, where the range of the ADC/DAC card is 0 to $+K$ volts.

EXERCISE 7

When the input to op-amp 1 ranges between 0 and +10 V the desired output of op-amp 2 is −6.5 and +6.5 V, respectively. Use equation 5 to show that $V_{off} = -2.83$ V and $R_2 = 1.3R_1$.

If the above values of V_{off} and R_2 are used, the circuit in Figure 11.8 will provide an accelerating sawtooth voltage ranging from 0 to +40 V as the input sawtooth ranges from 0 to +10 V. The period of the sawtooth is determined by the time per centimeter setting on the horizontal oscilloscope sweep.

Bench test the circuit before connecting it to the Franck–Hertz tube. The test should include observing the collector voltage on the oscilloscope as the time per centimeter setting is changed. If the circuit is functioning properly turn the voltages off and connect the circuit to the Franck–Hertz tube.

Connect the output of the electrometer to the oscilloscope vertical input. Bring the Franck–Hertz tube to a temperature of about 175 °C and then apply voltages. If a Polaroid camera is available photograph the oscilloscope screen, which should resemble Figure 11.4.

Disconnect the electrometer from the oscilloscope and connect it to an *xt* chart recorder. Record the data on the chart recorder and then analyze it.

When running the experiment the time per centimeter setting of the scope will be determined by the response time of the electrometer. For the H-P 425A instrument the oscilloscope sweep must be about 1 s/cm or longer, and for the Keithley 610C it may be about 10 ms/cm or longer.

EXERCISE 8

Suppose you wanted to carry out this experiment such that the data recorded correspond to the ${}^1S_0 \rightarrow {}^1P_1$ transition, rather than the ${}^1S_0 \rightarrow {}^3P_1$ transition. What tube temperature would be required to do this? To answer this question calculate the ratio of pressure to temperature required to observe current maxima separated by 6.7 eV, corresponding to the ${}^1S_0 \rightarrow {}^1P_1$

transition, and then use a mercury vapor pressure table to determine the values for pressure and temperature that satisfy the ratio. You may assume the mercury gas is an ideal gas and that the accelerating voltage is 30 V. Also, to calculate the electric field E you will need to know (or approximately measure) the distance from the cathode to grid 2.

OPTIONAL: COMPUTER-ASSISTED EXPERIMENTATION

Prerequisite

Experiment 6, Introduction to Computer-Assisted Experimentation.

Experiment

This experiment will utilize two conditioning circuits, one that couples the output of the experimental apparatus to the ADC input and another that couples the output of the DAC to the apparatus, providing the accelerating voltage. The circuit that couples the apparatus to the ADC will be discussed first. Also, this experiment involves voltage measurement and you may want to review such measurements as described under Hall Effect Voltage, Experiment 6, Introduction to Computer-Assisted Experimentation.

In Experiment 6 it was pointed out that the conditioning circuit depends on the analog range of the ADC/DAC card and the maximum voltage output of the experimental apparatus, in this case specified as $V_{\mathrm{E,\,max}}$. The circuits shown in Figures 11.9*a* and *b* are for analog ranges of $-K$ to $+K$ and 0 to $+K$, respectively.

Consider the circuit for an analog range of $-K$ to $+K$ volts, Figure 11.9*a*. The output of the op-amp is given by

$$V_{\mathrm{out}} = -\frac{R_2}{R_1}V_{\mathrm{E}} + \frac{R_1 + R_2}{R_1}V_{\mathrm{off}} \qquad (\mathrm{V}) \tag{6}$$

where V_{E} is the electrometer output.

EXERCISE 9

Assuming $V_{\mathrm{E,\,max}} = -1$ V and $K = 5$ V, show that $R_2 = 10R_1$ and $V_{\mathrm{off}} = -0.455$ V.

The circuit shown in Figure 11.9*b* is for an ADC/DAC card with an analog range of 0 to $+K$ volts. The output of the op-amp is

$$V_{\mathrm{out}} = -\frac{R_2}{R_1}V_{\mathrm{E}} \qquad (\mathrm{V}) \tag{7}$$

where R_2 is chosen such that the range of the output is 0 to $+K$ volts.

It is good laboratory procedure to bench test a circuit before using it in an experiment. To do so, replace the electrometer in Figure 11.9 with the circuit shown in Figure 11.10, and connect the output of the op-amp to a voltmeter.

The analog output of the DAC can be used to control dc voltages for the Franck–Hertz tube. For an analog range of $-K$ to $+K$ volts the circuit in Figure 11.5 may be used, where the 10-kΩ potentiometer system is replaced with the analog output of the DAC. For an analog range of 0 to $+K$ volts the circuit in Figure 11.8 is adequate, where the oscilloscope–potentiometer system is replaced with the analog output of the DAC. In either circuit it is likely that you will have to change the value of R_2.

Interface the Franck–Hertz tube to the computer using the two circuits that are

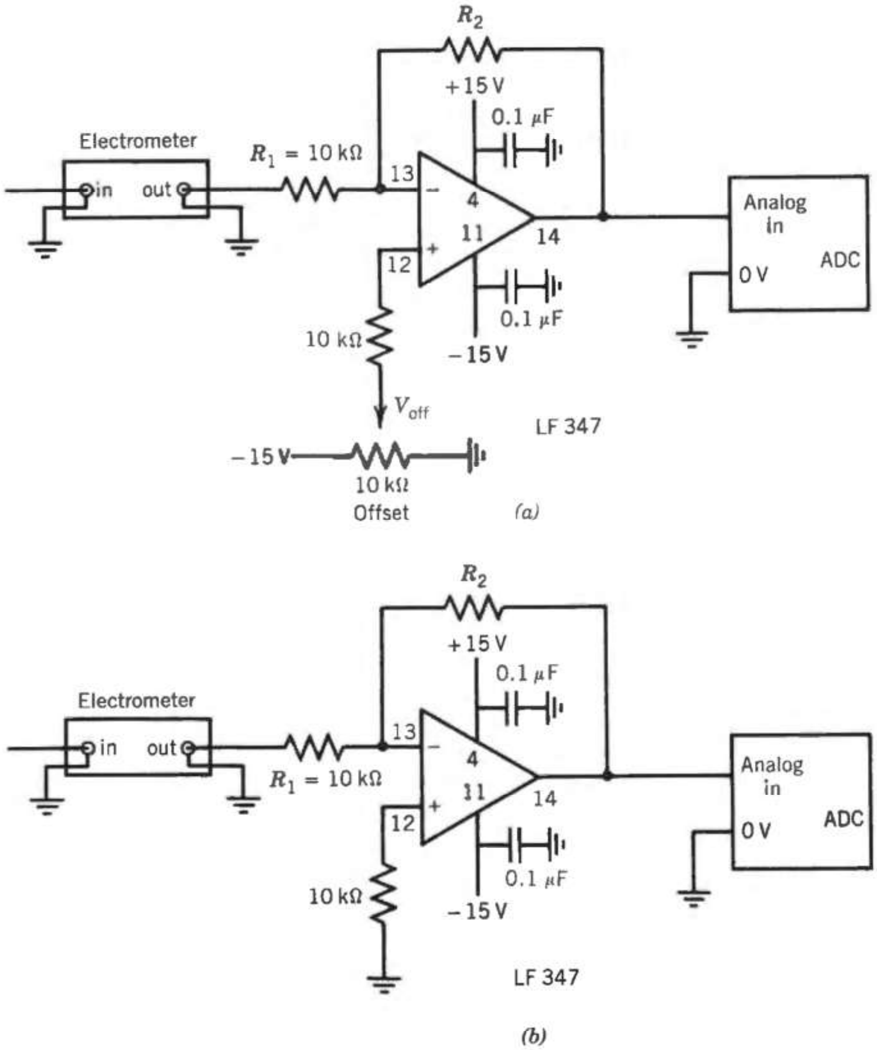

FIGURE 11.9 Conditioning circuits for an ADC/DAC card with analog range (*a*) from $-K$ to $+K$ volts, and (*b*) from 0 to $+K$ volts.

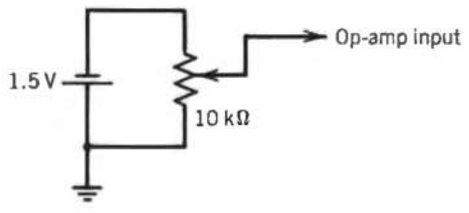

FIGURE 11.10 Input for bench testing either circuit in FIGURE 11.9.

appropriate for the analog range of your ADC/DAC card. Some possible things you can do are the following:

1. Write software that increments the accelerating voltage, reads the ADC input voltage for each accelerating voltage, and stores each pair of values. Also write software that plots and analyzes the data.
2. Instruct the computer to print a hard copy of the data and analysis.