Theory

At the turn of the century, spectroscopic work had clearly shown that atoms absorbed and emitted radiation at discrete frequencies (and therefore discrete energies). As explanation for these experimental facts, Niels Bohr postulated that the electrons in an atom could only exist in certain energy states and that the amounts of radiative energy absorbed or emitted corresponded to the difference in energy between the allowed energy levels as the electrons made transitions between them. Despite Bohr's success at explaining the spectrum of hydrogen using his hypotheses, there were still questions as to the reality of discrete energy levels.

In 1914 Franck and Hertz provided further evidence to support Bohr's hypotheses by showing that excitation to the same energy levels already determined spectroscopically could also be achieved by bombarding the gas with electrons. In other words, they showed that no matter how the atoms received the energy, (whether through interaction with a somewhat mysterious photon or through collision with a "real" particle, the electron), they could only accept it in certain amounts, namely those that bring the total energy in the atom to one of its allowed levels.

This experiment is a modern version of the one Franck and Hertz performed. It is divided into two parts. In the first part you will use an apparatus similar to the one used by Franck and Hertz to measure the first excitation potential and the ionization potential of mercury. In the second part, in order to present further evidence in support of discrete energy levels in atoms and excitation by electron bombardment, you will use a slightly different method and apparatus to measure several excitation potentials and the ionization potential of helium.

The Franck-Hertz Experiment

A schematic diagram of the apparatus used by Franck and Hertz is shown in figure 1 at the top of the next page. A current passed through the filament heats the cathode giving electrons near its surface enough energy to escape into the evacuated tube. A variable potential, $V_a$, (positively biased wrt the cathode) applied to the grid accelerates the liberated electrons down the tube towards the collector which is mounted in such a way as to collect the electrons that get through the wire mesh of which the grid is made. A small potential, $V_r$, (negatively biased wrt the grid) applied between the collector and the grid opposes the advance of the electrons. Therefore, if the tube is highly evacuated, all the electrons have energy $e(V_a - V_r)$ when collected at the collector. (Actually, not all of the electrons have that energy. Why?) The galvanometer in the grid-collector circuit measures the magnitude and direction of the resulting collector current.
Now if some gas is introduced into the tube, the electrons will collide with the gas atoms on their way to the collector. Quantum theory states that if the electrons have less energy than that required to raise these gas atoms from their ground state to the first excited level, then an energy transfer between a colliding electron and the atom can not take place. Thus, although an electron may bounce around from atom to atom a good deal, it will not lose any energy in the process and will have $eV_a$ joules when it gets to the grid and be collected at the collector with energy $e(V_a - V_r)$. In other words, the collisions will be completely elastic. If, however, $V_a$ is raised until $eV_a$ becomes equal to the energy difference between the ground and first excited levels, then an energy transfer can take place in a collision. The colliding electron will lose all of its energy to the atom which is accordingly raised to its first excited state. Such an electron no longer has enough energy to make it to the collector and there is a decrease in the collector current. These inelastic collisions would take place at the grid. (Why?) If $V_a$ is increased further, then the point at which the collisions change from elastic to inelastic will move towards the cathode. Electrons momentarily brought to rest by the collision will be accelerated again towards the grid. The collector current will begin to rise again from the dip observed when $eV_a$ was just equal to the energy difference between the ground level and the first excited level. If $V_a$ is raised even further there will come a point at which an electron has a collision in which it loses an energy equal to the atom's first excitation energy and then gains enough energy from the second acceleration to make a second inelastic collision in which it loses another identical package of energy. Again the electron will not have enough energy to get over the potential barrier, $V_r$, and there will be a second decrease in the collector current. Thus, as $V_a$ is increased we will find a dip in the collector current when ever $V_a$ is equal to an integral multiple of the first excitation potential of the gas used in the tube. A typical plot of collector current vs accelerating potential is shown in figure 2.
Note that the correct value of the first excitation potential is obtained by measuring between the adjacent dips rather than between the first dip and $V_a = 0$ because the actual potential between grid and filament must include the contact potential between the electrodes. In determining the excitation potential as the difference in $V_a$ between adjacent dips we are in effect subtracting the potential required for $n$ inelastic collisions from that required for $(n+1)$ collisions. Since the contact potential is present as an additive constant in both these quantities, it subtracts out.

The same apparatus can be used for the measurement of the ionization potential, the energy required to remove an electron completely from the atom. To do this, the collector is biased slightly negatively wrt the cathode so that no electrons can reach the collector. The positive ions formed when ionization takes place are collected instead. As the accelerating potential is increased, the ion current as measured by the galvanometer stays at or close to zero until the accelerated electrons have enough energy to ionize the gas atoms. When that point is reached, there is a sharp increase in the collector current due to ionization from the bombarding electrons and from an avalanche effect of the ejected electrons ionizing still more atoms and so on. As with the first excitation level, the measured energy must be corrected for the contact potential.

**The Critical Potentials of Helium**

A schematic diagram of the apparatus used for this part of the lab is shown in figure 3a. Its operation is similar in many respects to the Franck-Hertz tube described above. As current is passed through the filament-cathode, electrons are boiled off and accelerated towards the wide part of the tube by a variable potential, $V_a$, applied between the cathode and the anode. The anode is constructed so that a narrow cone of electrons is emitted into the main portion of the bulb. The bulb itself is coated with a transparent conducting material which is connected to the anode making
the main portion of the tube free of electric fields. Therefore, the energy of the electrons in this region is eV_a. The tube is filled with helium at low pressure. The collector is a wire ring so positioned that it cannot receive electrons directly from the cathode.

![Diagram](Image)

Figure 3

An electron in the field free region of the bulb with energy just sufficient to excite an atom will, after collision, have little or no residual energy and will eventually diffuse to the walls and be returned to the cathode. By making the collector a few volts positive wrt the anode such an electron will be attracted to it and be collected. A galvanometer is included in the collector circuit to monitor the number of these low energy electrons. A typical curve made with this apparatus is shown in figure 3b. An explanation of its shape is given below.

As V_a is increased from zero, the beam current also increases following a diode characteristic. Some electrons are elastically scattered out of the beam and reach the collector ring. Therefore, the collector current also increases following a similar diode characteristic. When the mean energy of the electron stream is sufficient to excite the helium from its ground state to its first energy level above the ground state, the collisions become inelastic; the population of low energy electrons increases significantly and a moderately sharp rise is recorded in the collector current. (Note: In an ideal experiment, the collector current would rise abruptly at this point, but because of the range of energies present in the electron beam due to the nature and temperature of the cathode, the increase is more gradual.) As the accelerating potential is increased further the collector current reaches a maximum and begins to fall. This decrease is partly due to the fact that the amount of residual energy that the electrons have after collision is also increasing so that capture by the collector is lessened; and partly due to the fact that the fraction of excitations per collision tends to fall off once the critical potential has been exceeded. As the accelerating potential is further increased, the electrons eventually have just enough energy to raise the gas atoms to the next higher energy level. The percentage of inelastic collisions, and therefore the population of low energy electrons, increases and the collector current again shows a sharp rise. Once the critical potential is exceeded, the current again shows a dip. This pattern is repeated until the ionization potential is reached resulting in a
steadily rising collector current due to the vastly increased population of electrons.

The ionization potential of helium can also be measured by reversing the polarity of the collector and collecting the ions rather than the electrons. A sharp rise in the ion current marks the onset of ionization. As with the Franck-Hertz experiment, both the measured excitation potentials and the measured ionization potential must be corrected for the contact potential in order to get their actual values.

The principal energy levels of helium and their critical potentials are shown in figure 4. Although nine critical potentials are listed, one of which is the ionization potential, the energy differences between some levels are so small that the recording of the differences is washed out by the variations in emission velocities of the electrons. Transitions from the ground state \(1^1S\) to \(2^1S\), \(2^3P\) and \(2^1P\) levels may be expected to appear as one potential as do those to \(3^3S\), \(3^1S\), \(3^3P\) and \(3^1P\) levels.

<table>
<thead>
<tr>
<th>Ground-state</th>
<th>(1^1S) - zero eV</th>
<th>(2^1S) - 20.61 eV</th>
<th>(3^3S) - 22.71 eV</th>
<th>ionization potential</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(2^3P) - 20.96 eV</td>
<td>(3^1S) - 22.91 eV</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(2^1P) - 21.21 eV</td>
<td>(3^3P) - 23.00 eV</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(2^3S) - 19.80 eV</td>
<td>(3^1P) - 23.08 eV</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Average Values: 19.8 eV, 20.9 eV, 22.9 eV, 24.6 eV

Figure 4

References

Besides the discussion given in your text, the following references will be helpful in answering the questions at the end of the lab. All are on reserve in Kresge library.

1. Harnwell and Livingood, Experimental Atomic Physics (McGraw Hill, N.Y., 1933)
3. Novel Experiments in Physics, II@ (AAPT Committee on Apparatus, N.Y., 1975)
Procedure

Before beginning, please note the following:

a. All equipment settings given are nominal settings. You will most likely have to vary the settings somewhat to get the optimum performance from your equipment.

b. The oven for the Franck-Hertz tube used in measuring the ionization potential (part II) takes approximately one hour to come to the proper operating temperature. If you are going to do all three parts at one sitting, it is advisable to turn on the oven for that part at the beginning of the session. Then by the time you are ready to do part II, the oven should be ready to use.

c. Always make certain the Franck-Hertz tubes are at the proper operating temperatures before applying any voltages to the various connections. Always approach the temperature at which you plan to make the ionization potential measurement from the high side with the filament on so that the mercury will not have a chance to short the tube by condensing between the cathode and $g_1$.

d. With the Franck-Hertz tubes, never allow the accelerating potential to go above 35 volts. Otherwise, a gas discharge might occur which could potentially damage the power supply.

e. On the newer x-y recorders, both the LINE switch and the SERVO switch must be on before the pen can be moved by any of the controls or by an incoming signal.

The CHART HOLD switch puts an electrostatic charge on the paper, thereby holding it in place. To remove the graph paper, deactivate that switch.

The PEN switch allows you to lower and lift the pen from the graph paper. Careful use of this switch to lift the pen from the paper when you are done making a plot will prevent inadvertent destruction of the plot by dragging the pen back across the graph when returning the accelerating potential to 0.0 volts.

If the pen on the x-y recorder attempts to go beyond its limits, the x-y recorder will begin to whine. Do not let this continue for any length of time as it will eventually either cause a belt to break or cause the motor to burn out.

Part I - Measurement of the Excitation Potential of Mercury

The apparatus for this part consists of the following:

a. Franck-Hertz tube with oven: identical in construction and operation to the one described in the introduction; the oven has a window in the back for direct observation of the tube;

b. a power supply containing jacks for the filament current (nonvariable), the accelerating voltage (variable 0-50 volts) and the retarding potential (variable 0-5 volts);
c. a Keithley nullmeter - used to monitor the collector current by recording the voltage across a 1MW resistor through which the collector current flows; also amplifiers this voltage to make it easier to output to the x-y recorder;

d. a helipot to allow for finer control of the accelerating potential;

e. an x-y recorder on which to record the collector current vs accelerating potential graphs; measurement of the first excitation potential and the ionization potential of Hg will be made directly from these graphs; and

f. a multimeter; all voltage settings should be made with this to increase the accuracy of results.

1. Plug in the oven and set the temperature control on the side to read 180. (Note: The numbers on the dial do not correspond exactly to temperature settings. Some readjustment of the dial may be necessary to get the oven to the proper operating temperature which is between 170 and 190 degrees.) Insert the thermometer into the hole provided for it in the top of the oven, positioning the bulb so that it is even with the mid-section of the Franck-Hertz tube. Make certain that all of the electrical equipment is turned off, that all of the voltage controls on the power supply are turned to zero (full counterclockwise) and that the dial on the helipot is set to zero. Wire the apparatus according to figure 5.

2. When the oven has stabilized at approximately 180 degrees, turn on the power supply and use the multimeter to set the accelerating voltage to 30.0 volts and the retarding potential to -1.0 volt. (Note: Once the accelerating voltage on the power supply has been set to 30.0 volts, it
should not be changed. The helipot should now be used to vary the accelerating voltage in the tube. Turn on the x-y recorder and set the x-scale to the vernier setting between the 1 V/in and the 10 V/in settings. Insert a piece of 10 divisions/in graph paper and activate the chart hold switch. Use the x-vernier control, the x-zero control, and the helipot to calibrate the x-scale so that when the accelerating voltage is 0.0 volts the pen point is exactly on the far left vertical line of the graph paper and when the accelerating voltage is 30.0 volts the pen point is exactly on the far right vertical line of the graph paper. Since the accuracy of your measurements will depend on the accuracy of this calibration, take your time when doing it. It is also a good idea to check the calibration during the experiment to assure that it has not inadvertently changed.

3. Set the accelerating voltage to 0.0 volts. Turn on the Keithley nullmeter and set the range to 30 millivolts full scale. Set the y-scale to the vernier setting between the 10 mV/in and the 100 mV/in settings and use the y-zero control on the x-y recorder to position the pen near the bottom of the graph paper. Moderately slowly, increase the accelerating voltage to 30.0 volts; and using the y-vernier, adjust the scale calibration so that at 30.0 volts the pen is near the upper right hand corner of the graph paper. (Note: During this sweep, the Franck-Hertz oscillations in the collector current should be easily seen. If they are not, go back and check the things you did in steps 1 and 2. If everything seems in order and you still do not see the oscillations as the accelerating voltage is varied, see Jan Largent.) Return the accelerating voltage to zero. You are now ready to take data.

4. Insert a clean sheet of graph paper and adjust the x-zero so that the pen rests on the left most vertical line when the accelerating voltage is 0.0 volts. Slowly increase the accelerating voltage to 30.0 volts. Repeat this step until you get a good, clean graph of the collector current vs accelerating voltage. Label the graph with all of the pertinent parameters.

5. Turn off the lights in the room. Without any paper in the recorder, vary the accelerating voltage from 0.0 volts to 30.0 volts and observe the tube through the window in the oven. Record your observations.

6. When done, set all of the voltage controls on the power supply to zero, turn off all of the equipment, unplug the oven, put the cap back on the recorder pen and unwire the apparatus.

Part II - Measurement of the Ionization Potential of Mercury

The apparatus for this part consists of the following:

a. Franck-Hertz tube with oven: this tube is different in construction from the tube used in part one in three ways - (1) it uses a cylindrical grid configuration, (2) it has an extra grid near the cathode to overcome space charge effects and (3) a short pin (marked S in the diagram) is fused into the glass press of the tube between the anode A and the grid g2 to pre-
vent leakage currents between those electrodes; the tube's construction and the key to the wires coming off the seven pin base is given in figure 6.

![Figure 6](image)

b. a power supply, helipot, multimeter, and x-y recorder; same functions as in part I;

c. Pasco electrometer; same function as Keithley nullmeter in part I; and

d. an HP 6215A power supply to supply the voltage for grid $g_1$.

1. Plug in the Variac, turn it on and set the dial to 50. This will bring the tube to the proper operating temperature to measure the first excitation potential and the contact potential for this particular tube. Insert the copper shield and then the Franck-Hertz tube into the oven. Turn on the Pasco electrometer. Make certain that all of the electrical equipment is turned off (except for the electrometer which needs time to warm up and stabilize), that all of the voltage controls on the power supply are turned to zero and that the dial on the helipot is set to zero. Wire the apparatus according to figure 7.

![Figure 7](image)
2. After one hour, turn on the power supply and use the multimeter to set the accelerating potential to 30.0 volts, the retarding potential to -1.0 volt, and the potential on grid g|l\ to 1.0 volt. As in part I, all variations in the accelerating potential should now be done using the helipot. Turn on the x-y recorder and calibrate the x-scale in the same way as in step 2 of Part I.

3. Set the accelerating potential to 0.0 volts. On the Pasco electrometer: set the RANGE to 1, the METER (on the right side of the electrometer) to -, the MODE to 10^-9 A and the METER (on the left side of the electrometer) to external. Use the y-zero control on the x-y recorder to position the pen near the bottom of the graph paper. Moderately slowly, increase the accelerating voltage to 30.0 volts. Adjust the y-scale so that at 30.0 volts the pen is near the upper right hand corner of the graph paper. (Note: During this sweep, the Franck-Hertz oscillations in the collector current should be easily seen. If they are not, go back and check the things you did in steps 1 and 2. If everything seems in order and you still do not see the oscillations as the accelerating voltage is varied, see Jan Largent.) Return the accelerating voltage to zero. You are now ready to take data.

4. Insert a clean sheet of graph paper and adjust the x-zero so that the pen rests on the left most vertical line when the accelerating voltage is 0.0 volts. Slowly increase the accelerating voltage to 30.0 volts. Repeat this step until you get a good, clean graph of the collector current vs accelerating voltage. Label the graph with all of the pertinent parameters.

5. Set the dial on the Variac to 40, turn off the power supply, turn all the voltage settings on the power supply to zero, and remove the Franck-Hertz tube from the oven. Rewire the apparatus according to figure 8.
6. Put the Franck-Hertz tube back into the oven and turn on the power supply. Using the multimeter, set the accelerating potential to 15.0 volts and the collector voltage to 1.0 volt. Calibrate the x-scale of the x-y recorder so that when the accelerating potential is 0.0 the pen point is exactly on the far left vertical line of the graph paper and when the accelerating potential is 15.0 volts the pen point is exactly on the far right vertical line of the graph paper.

7. Insert a clean sheet of graph paper and adjust the x-zero so that the pen rests on the left most vertical line when the accelerating voltage is 0.0 volts. Slowly increase the accelerating voltage to 15.0 volts or until the pen starts to go off the vertical scale. Repeat this until you get a good, clean graph of the ion current vs accelerating potential. Label the graph with all the pertinent parameters.

8. When done, set all of the voltage controls on the power supply to zero, turn off all of the equipment, unplug the Variac, remove the Franck-Hertz tube from the oven, put the cap back on the recorder pen and unwire the apparatus.

Part III - Measurement of the Critical Potentials of Helium

The apparatus for this part is the same as in parts I and II. The only differences being that there are separate power supplies for each potential. The critical potentials tube is identical to that described in the introduction.

1. Make certain that all of the electrical equipment is turned off and that all of the voltage and current controls on the power supplies are set to zero. Wire the apparatus according to figure 9.
2. Turn on the HP 6282A and switch the meter to the 12 amp position. Turn the voltage control knob full clockwise. Using the current control knob, set the current to 1.5 amps. (Note: Until the tube is thoroughly warmed up, the current will tend to get gradually larger. Keep adjusting it to 1.5 amps until it stabilizes. Too high a filament current may burn it out.) The filament in the tube should now be glowing. Set the accelerating potential power supply to 25.0 volts and the collector potential power supply to 1.0 volts. As in part I, all variations in the accelerating potential should now be done via the helipot. Turn on the x-y recorder and calibrate the x-scale so that when the pen point is on the left most vertical line the accelerating potential is 0.0 volts and when the pen point is on the right most vertical line the accelerating potential is 25.0 volts.

3. Return the accelerating potential to 0.0 volts. Turn on the Keithley and set the range to 3 volts full scale. Moderately slowly, increase the accelerating voltage to 25 volts and adjust the y-scale controls so that the pen stays on scale throughout the entire sweep. You should see the pen trace out a pattern similar to the one seen in figure 3b. If you do not, check the things you did in steps 1 and 2 above. If you still experience difficulty, see Jan Largent.

4. Insert a clean sheet of graph paper and adjust the x-zero so that the pen rests on the left most vertical line when the accelerating voltage is 0.0 volts. Slowly increase the accelerating voltage to 25.0 volts. Repeat this step until you get a good, clean graph of the collector current vs accelerating voltage. Label the graph with all of the pertinent parameters. This graph gives you an overall picture of the collector current vs accelerating potential curve.

5. Recalibrate the x-scale so that the two extreme vertical lines of the graph paper represent 15.0 and 25.0 volts respectively. Insert a clean sheet of graph paper and adjust the x-zero so that the pen rests on the left most vertical line when the accelerating voltage is 15.0 volts. Slowly increase the accelerating voltage to 25.0 volts. Repeat this step until you get a good, clean graph of the collector current vs accelerating voltage. Label the graph with all of the pertinent parameters.

6. Reverse the banana leads on the power supply supplying the collector potential. The collector now has a negative potential wrt the anode and will collect positive ions.

7. Insert a clean sheet of graph paper and adjust the x-zero so that the pen rests on the left most vertical line when the accelerating voltage is 0.0 volts. Slowly increase the accelerating voltage to 25.0 volts. Repeat this step until you get a good, clean graph of the ion current vs accelerating voltage. Label the graph with all of the pertinent parameters.

8. Set the collector potential to zero and repeat step 7.

9. When done, set all of the voltage controls on the power supplies to zero, turn off all of the equipment, put the cap back on the recorder pen and unwire the apparatus.
Part IV (optional) - Suggestions For Further Work

For those ambitious souls among you who might want to earn some extra credit, the following activities are suggested. Investigate the effect of operating the tubes at other than the previously suggested voltage and temperature settings. However, do not exceed the manufacturer's suggested current, voltage and temperature limits without good cause plus grave consultations with Jan Largent. With the Franck-Hertz tubes, one particularly interesting subject is the relationship between the tube temperature and the peak spacing. You might also try to rewire the circuit to look for other critical potentials -- these measurements should be done at a lower temperature.

Lab Report

Your lab report will be your lab notebook. It should be a complete record of what you did in the lab. In recording your data, think in terms of perhaps having to return to the book some months or years hence, and being able to understand what you were doing, what you observed and what your conclusions were. All the data for the lab, all the calculations, tabulations and comments should be written in the notebook. If you make an incorrect calculation, don't erase it - mark through it and redo it. Ideally, your notebook should be a clear record of what you did in the lab and what was done later.

Include the following in your lab report.

Parts I and II

1. your plots of collector current vs accelerating potential for both tubes and your plot(s) of ion current vs accelerating potential from the second tube;

2. computations of the contact potentials in volts for both tubes;

3. computation of the average value of the first excitation potential of mercury in both volts and wave numbers as measured from your plots - don't forget to adjust this for the contact potential - with a comparison between your experimental value and the accepted value;

4. computation of the ionization potential of mercury in volts as measured from your plots with a comparison between your experimental value and the accepted results; and

5. the answers to these questions:

   a. What is the mean free path of an electron in a Frank-Hertz tube heated to 100 C? 150 C? 200 C? (There is enough mercury in the tube to assure that some liquid is always present. The vapor pressure of mercury at various temperatures can be found in the Handbook of Chemistry and Physics.) Compare these mean free paths with a cathode-accelerating grid
spacing of 8 mm. What can you say about the likelihood of ionization at each of these three temperatures? Assume an accelerating voltage of 30 volts and clearly state any assumptions that you make.

b. All electrons are emitted from the cathode with non-zero velocities. Make an estimate of the uncertainty in the excitation and ionization potentials you measure due to this effect.

c. Why do the gaseous mercury atoms only get raised to their first excited state?

d. When the excited atoms in the two parts of the experiment return to the ground state, they give off radiation. In either part of the experiment, would you expect to see the radiation coming from the respective tubes as you increased the accelerating voltages through their ranges? Explain your answer.

e. What would you expect to find in the way of radiation when the atoms are being ionized? Should you be able to see the anything? Explain your answer.

f. What is the effect on peak location of the general upward trend of the curve? Is there a trend in the peak spacing? Can you account for it by considering the relationship between the voltage on the grid and the voltage measured by $V_2$?

g. In the ionization plot, the ion current shows a slight increase in the ion current before the sharp increase indicating the onset of ionization. Explain that small increase in ion current.

**Part III**

1. your plots of collector current vs accelerating potential and of ion current vs accelerating potential;

2. an explanation of the shape of the ionization plots;

3. computations of the contact potential in volts;

4. computation of the average value of the critical potentials of helium in both volts and wave numbers as measured from your plots - don't forget to adjust this for the contact potential - with a comparison between your experimental values and the accepted values; and

5. computation of the ionization potential of helium in volts as measured from your plots with a comparison between your experimental value and the accepted results.