

## Ph 3455

# The Franck-Hertz Experiment

### Required background reading

Tipler, Llewellyn, section 4-5

### Prelab Questions

1. In this experiment, we will be using neon rather than mercury as described in the textbook. In neon, there is an excited electron state at 18.9 eV above the ground state. What accelerating voltage will we need to apply to the electrons in the Franck-Hertz experiment to see a decrease in the collected current resulting from the excitation of this state in inelastic collisions?
2. After the state at 18.9 eV is excited, it de-excites by the electron dropping to a lower state at 16.57 eV. A photon is emitted. What is its wavelength, and where does it occur in the electromagnetic spectrum?

### Introduction

The general theory behind the Franck-Hertz effect is in the required background reading (see above), so we will not repeat all the details here. In this lab you will be using helium and neon gas to study the Franck-Hertz effect. The energy levels of helium are listed in Table 1 and the energy levels of neon are listed in Table 2. We will describe how the Franck-Hertz effect works with a simple example in helium. The apparatus you will use will allow you to send electrons through helium gas with kinetic energies varying from 10 eV to 50 eV. The minimum energy needed to excite the helium atom from its ground state is 19.80 eV, which is the energy needed to excite the first excited level in helium. When the incident electrons are adjusted to have that kinetic energy, they will excite the helium atoms through inelastic collisions and then lose most of their energy. Your apparatus will be able to detect those inelastically scattered electrons. So you will see an increase in the number of detected electrons when you adjust the kinetic energy of the incident electrons to 19.80 eV. As you increase the kinetic energy of the incident electrons you will see further peaks at 20.61 eV, 20.96 eV, ... until the helium atom is finally ionized when you hit 24.58 eV. A similar thing will happen for neon. Finally, you will notice that you also see a group of peaks at around 40 eV (for helium). This corresponds to electrons that have undergone inelastic scattering **twice**. An example might be a 39.6 eV incident electron that excites the first excited state in one helium atom at 19.80 eV, reducing its energy to 19.80 eV. Then it can inelastically scatter with another helium atom reducing its energy to almost nothing, at which point our detector will detect it.

0 eV (ground state)  
 19.80 eV (1<sup>st</sup> excited state)  
 20.61 eV  
 20.96 eV  
 21.21 eV  
 22.71 eV  
 22.91 eV  
 23.00 eV  
 23.08 eV  
 24.58 eV (ionization energy)

Table 1: Energies of the excited states in helium (up to the ionization energy)

0 eV (ground state)  
 16.57 eV (1<sup>st</sup> excited state)  
 16.62 eV  
 16.66 eV  
 16.79 eV  
 18.38 – 18.97 eV (several levels in this range)  
 19.66 – 19.78 (several levels in this range)  
 20.3 eV  
 20.57 – 20.66 eV (several levels in this range)  
 21.56 eV (ionization energy)

Table 2: Energies of the excited states in neon (up to the ionization energy)

### Apparatus

A schematic of the apparatus is shown in Figure 1. Our apparatus works a little differently from that described in the textbook.

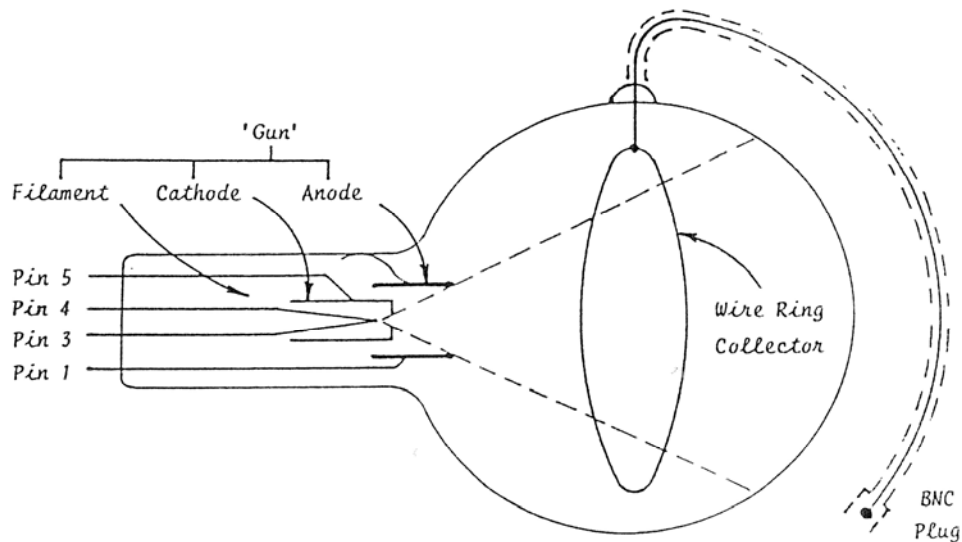


Figure 1: Schematic of the Hertz Critical Potentials Tube

The filament has a large (about 1 - 1.5 amp) current passing through it. It becomes hot and electrons are “boiled” off by thermionic emission. The electrons are accelerated by an anode held at positive potential (between 10 and 50 volts) relative to the cathode. Many of these electrons pass into the spherical bulb filled with low pressure helium or neon gas. Electrons which undergo only elastic collisions (collisions where they don’t lose kinetic energy) pass through and hit one of the glass walls. The glass walls have a transparent conductive coating connected to the anode so that charge doesn’t build up on the glass walls. The electrons that we are interested in are those that undergo inelastic collisions where they lose a significant amount of kinetic energy. An electron with just sufficient energy to excite an atom will, after the collision, have little or no residual kinetic energy and in the field-free region of the bulb will diffuse eventually to the walls and be returned to the cathode. By making the collector a few volts positive with respect to the anode such an electron will be attracted to it and collected. Thus when the mean energy of the electron stream is sufficient to excite helium atoms, the population of low energy electrons will increase significantly to produce in the collector a measurable current with little or no contribution from the main stream. As the accelerating voltage is increased the excitation at first increases and then falls away until another, higher energy, excitation occurs with a further increase in the low energy electron current.

The actual kinetic energy of the accelerated electrons is given by:

$$KE = e(V_A + V_0)$$

where  $V_A$  is the applied anode potential (in the 10 – 50 volt range) and  $V_0$  is the thermionic work function, which is in the 1-2 volt range for this apparatus.

## Procedure

In this lab you will use the digital oscilloscope to study the waveforms. In the first part of this lab, you will go through some steps to familiarize yourself with the operation of the oscilloscope. You will be using the Tektronix TDS 2014 oscilloscope; it is a four channel digital oscilloscope. One of the very nice features of the Tektronix TDS 2014 oscilloscope is its ability to be connected to a computer. This allows the computer to both control the oscilloscope and record data from it. You will use this feature to print the display of the oscilloscope.

Turn on the oscilloscope and go through the introduction to the most important controls below. Take time to locate each **bold-faced** item when it is mentioned.

Many of the functions of the Tektronix TDS 2014 oscilloscope are controlled by the use of menus. When a menu button is pressed the menu options for that button are displayed on the right side of the oscilloscope screen. Five selection buttons along the right side of the screen are used to select from the various menu options that are available. When the selection button next to menu item is pressed the option will toggle through several setting choices for that option. If the button is pressed enough times it will return to the original setting. There are three menu buttons that are of general use on the oscilloscope;

they are the **CH1**, **CH2**, **TRIG** menu buttons. In this part of the lab you will be exploring some of the functions in these menus as well as some of the other controls of the oscilloscope.

### **CH1 and CH2 Menu Buttons**

The oscilloscope has two channels (**CH1** and **CH2**) that can measure voltages independently. The settings for each of these channels are menu driven. By pressing the **CH1** or **CH2** menu button various options can be selected. Pressing the menu button once turns on the channel. Pressing the menu button a second time turns off the channel. When the channel is selected **CH1** or **CH2** appears above the menu indicating that the menu options will be applied to that channel. If two channels are turned on at the same time then one of the channels will be selected and its label (**CH1** and **CH2**) will appear above the menu option on the screen. To select the other channel simply press its menu button.

The options that are most important on the **CH1** and **CH2** menus are the ‘coupling’ and the ‘probe’ settings. The ‘coupling’ option has three settings, DC, AC, and Ground. In the DC setting you see the total signal voltage. In the AC position the DC (direct current) portion of the signal is “blocked” (i.e., the mean value of the signal is subtracted), which is useful if you want to investigate a small, time-varying signal sitting on a large DC voltage. In the Ground setting the input is grounded, so that you have a zero reference point. The probe setting should be set to “x1”. By default it comes up as “x10”; please set it to “x1”.

### **Channel Controls for Channels 1 and 2 (CH1 and CH2)**

Each channel (**CH1** and **CH2**) has the following set of independent controls:

- A gain setting that sets the number of **VOLT/DIVISION**. This value is displayed on the bottom of the oscilloscope screen.
- A vertical position control, above the **CH1** and **CH2** menu buttons.

### **Trigger (TRIG) Menu button**

The oscilloscope sweeps out a trace of the voltage as a function of time. The oscilloscope needs to know when to start this sweep. The trigger signal is the way the oscilloscope determines when to start the sweep. The **TRIG** menu button allows you to tell the oscilloscope what signal to trigger the sweep on and on what part of that signal. The options on the TRIGGER menu that are most often used are Type, Source, Slope, and Mode. The trigger Type option will always be set to ‘Edge’ in this lab but in other setting is useful when looking at special signal such as those from a video source. The trigger Source option is the voltage signal that will start the sweep. This signal can come from either **CH1** or **CH2**, an external line, or from the 60 Hz AC power sources. Usually the trigger signal will come from **CH1** or **CH2**. The Slope option allows the sweep to be

triggered either when the trigger signal is rising or falling. In this lab triggering on the rising signal will work for all the cases we will do. The Mode option has two settings: Auto and Normal. In the Auto setting the trigger is automatic so that the sweep display is visible even if there is no input signal. This is most useful for setting up and for looking at DC voltages. When the Mode option is set to Normal the sweep starts only when the trigger source changes as was selected in the other setting.

## Trigger Controls

The level of the signal that triggers the sweep can be adjusted by using the trigger Level knob. A small arrow appears on the right side screen indicating the level of the trigger voltage on the trigger sources (**CH1** and **CH2**). The **SET TO 50%** sets the trigger level automatically to 50% of the current trigger source. This is a very convenient feature to find an appropriate trigger level. The **FORCE TRIG** button forces the oscilloscope to trigger in Normal mode even if it doesn't see a trigger signal on the source. The **TRIG VIEW** button allows the trigger setting to be displayed on the bottom of the screen.

Before moving on, set the scope settings as follows:

- Select channel 1 by pressing the **CH1** menu button
- Press the “Coupling” menu until AC is displayed
- Press the “Probe” menu until “x1” is displayed
- Select channel 2 by pressing the **CH2** menu button
- Press the “Coupling” menu until AC is displayed
- Press the “Probe” menu until “x1” is displayed
- Press the **TRIG MENU** button and select **AUTO** trigger mode
- Press the “**SET TO 50%**” TRIGGER LEVEL button
- Set the horizontal sweep rate (sec/div) to 250  $\mu\text{sec/div}$ , the value is displayed on the bottom of the screen next to an “M”

You should see two flat scope traces; if you don't adjust the position knobs for each channel. Adjust CH1 so that it is at two major divisions above the center of the screen grid. Place the CH2 trace at two major divisions below the center of the grid. It is a good practice to keep the CH1 trace on the upper half of the display and the CH2 trace on the lower half.

## Function Generator

In its basic application, a function generator produces a repeating voltage pattern, where you may select on of several forms, the amplitude, and the frequency. You will be using the BK Precision 4017A Function Generator. Turn it on and set the following settings on the front panel:

### FREQUENCY

**Range selection**

Depress 1K button

**Coarse/fine controls**

Adjust for digital readout of 1000 Hz

(note that there is a delay in the response)

<b>Function</b> (not labeled with words only symbols)	Depress the button for sine wave.
<b>Duty Cycle</b>	off (button out), ignore the knob settings
<b>CMOS LEVEL</b>	off (button out), ignore the knob settings
<b>DC OFFSET</b>	off (button out), ignore the knob settings
<b>-20 dB</b>	off (button out), ignore the knob settings
<b>OUTPUT LEVEL</b>	Rotated knob to the center position

Use a cable (with BNC connectors on both ends) to connect the output of the function generator to CH1 of the scope. You should now see a signal on one trace and no signal on the other. Initially the signal will probably not be triggered properly, so it will appear “free-running” or random. Set the trigger **MODE to NORM** and to trigger on CH1. When you are in this configuration, a horizontal sweep will be initiated whenever the signal in CH1 passes a certain voltage level. To set this level, turn the LEVEL knob until you achieve a stable trace. As you turn the LEVEL knob, notice how it affects the point where the trace starts (the trigger level). Also, try changing the SLOPE that you trigger on from Rising to Falling on the TRIG MENU. When the scope is triggered properly, it will say “Trig’d” at the top; when it is not triggered it says “Ready”.

Select Channel 1 and change the “Coupling” to DC. Adjust the gain and vertical position so that the sine wave amplitude fits in the screen and is centered vertically.

Also try the cursor button to set a cursor to measure time differences; ask your TA for help on how this works.

Here is the procedure for capturing oscilloscope waveforms on the computer:

1. Under programs, open the OpenChoice Desktop software.
2. Click on “Select Instrument”
3. Highlight “ASRL1::INSTR”
4. Click on “OK”
5. Click on “Screen Capture”
6. Click on “Get Screen”. This operation takes 1-2 minutes; if it fails just try clicking “Get Screen” again.
7. Click on “Copy to Clipboard.”
8. Start a Word document where you can paste all of your images from this lab. Go ahead and paste the image of whatever is on the scope at the moment.

Now we will begin making measurements:

1. The apparatus should already be wired up. A diagram of the wiring is shown in Figure 2, but you only need to go through it in detail if things aren’t working. If you are having problems getting things to work, please consult with your TA.
2. First make sure the helium tube is installed. Your TA will help you determine which is which. Please be very careful with the tubes; put them in their holders. Only your TA should install and remove the tubes.

*Note: Be sure the filament supply voltage is floating.*

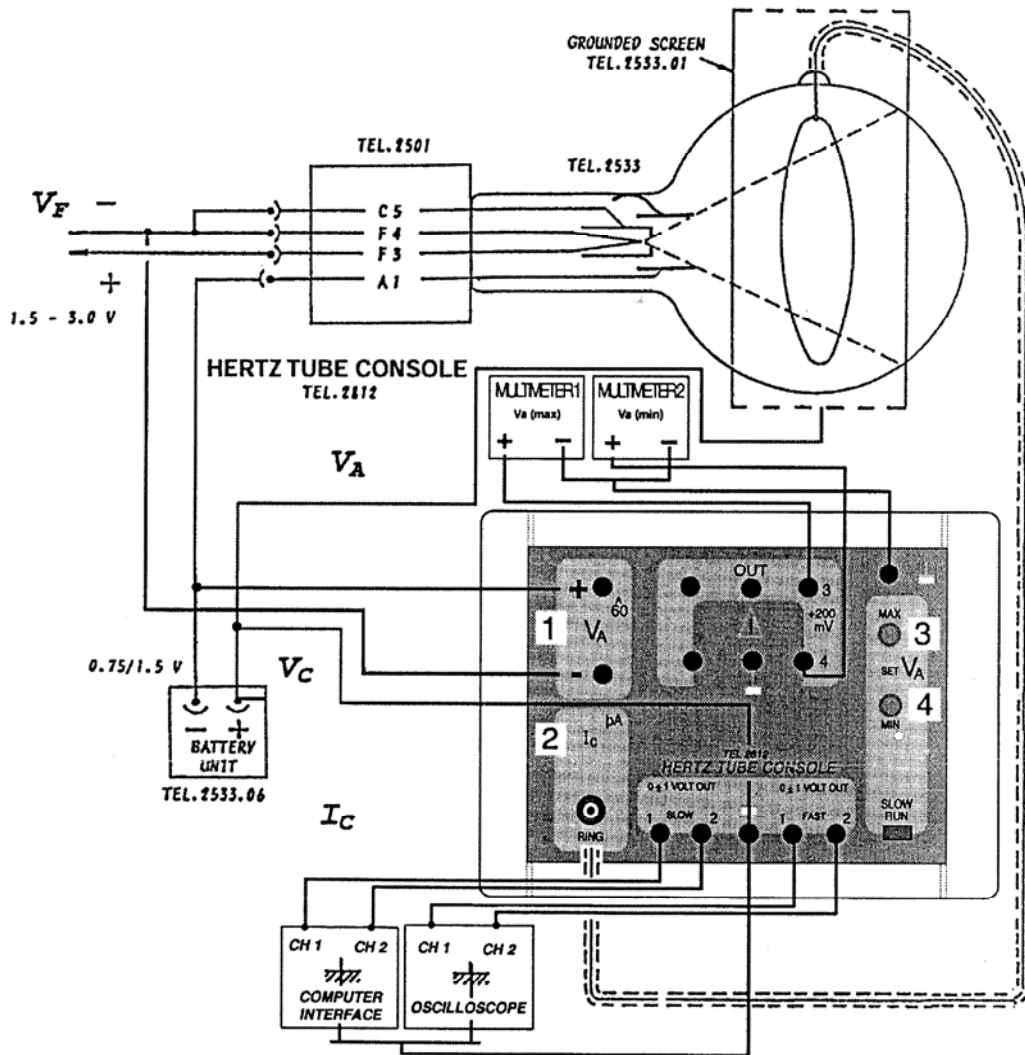


Figure 2: Electronic connections for the Hertz Console unit (if you need to adjust these connections, consult with your TA).

3. Locate the power supply to the filament (ask your TA if you aren't sure which one it is). Before turning this on, check that the voltage knobs (fine and voltage) are all the way down (counter-clockwise). The current knob should be all the way up (clockwise). We will run this power supply in "voltage control" mode meaning the adjustments are made using the voltage knob, and the power supply will provide whatever current is needed at that voltage (up to the limit of the supply). You can read the voltage and current on the

front of the supply. **Please don't go above 1.5 A on the current or 5.0 V on the voltage.**

4. Turn on the filament supply. Adjust the voltage to about 3 volts; if you look inside the glass tube, you should see the filament glowing. If it is not glowing, ask your TA for help. If it is working then turn it down to about 1.5 volts for now.

5. On the Hertz tube console, locate the dials that say MAX and MIN. Turn on your two digital multimeters and make sure they are set to DC voltage mode. Vary the MIN knob and see which multimeter changes; do the same for the MAX knob. These values are the minimum and maximum values of the accelerating potentials applied to the anode (you have to multiply the values on the multimeter by 1000 to get the correct values; ie 10 mV means 10 volt anode potential). The Hertz console sweeps the anode voltage rapidly between these two values over and over using a linear ramp. Hook the output of this linear ramp to channel 1 of the oscilloscope. Take a look at it and adjust the oscilloscope settings so that it looks like Figure 3. **(For CH1, make sure the "Coupling" switch is set to "DC". It may still be set at "AC" from earlier in the lab.)**

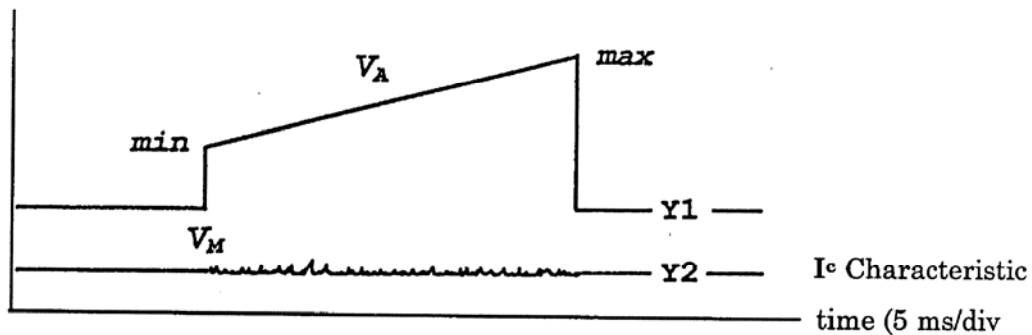


Figure 3: Expected output on the oscilloscope. The expected channel 1 signal is in the upper trace, and the expected channel 2 signal is in the lower trace (shown before the filament is turned on).

6. Channel 2 of the oscilloscope is connected to show the current collected by the ring (the current collected by the ring is converted to a voltage via a resistor). We are actually measuring very small currents here (picoamps), so the output will be somewhat noisy.

7. We will first do a broad exploratory scan in helium. Set the MIN voltage to 10 V and the MAX voltage to 50 V. Make sure the 1.5 V in the battery holder is connected with + to + and - to -. Make sure that the red connectors are in the "-" output on the battery holder (they may still be in the "B" output from the last group). If you are unsure about this, ask your TA.

8. Watch the display on channel 2 of the oscilloscope. Slowly increase the filament voltage until you see a pattern like that show in the left half of Figure 4. **(For CH2, make sure the "Coupling" switch is set to "DC". It may still be set at "AC" from earlier in the lab. Also, make sure CH2 is on "x1" probe and INVERT is on.)**



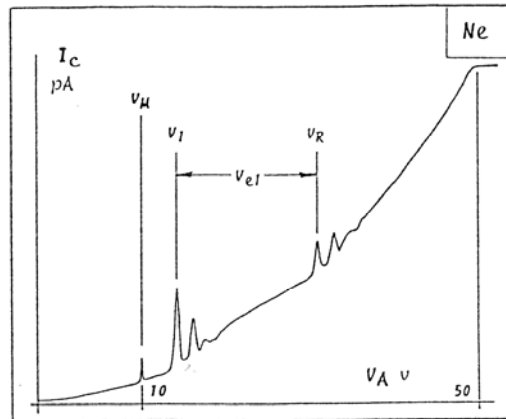
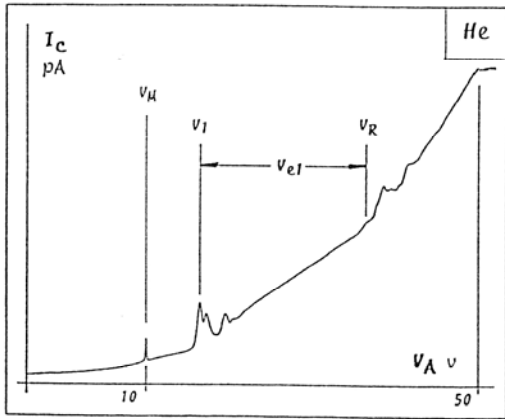


Figure 4: Broad exploratory scan (helium is on the left, neon is on the right).

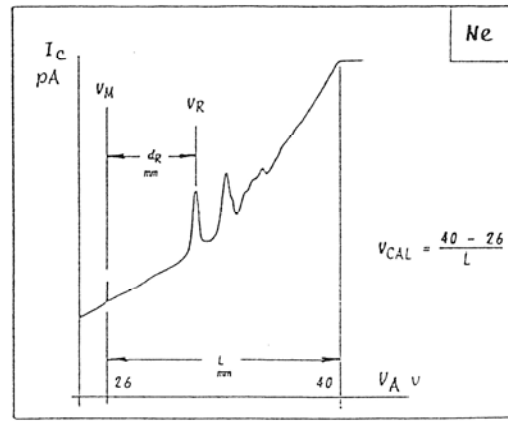
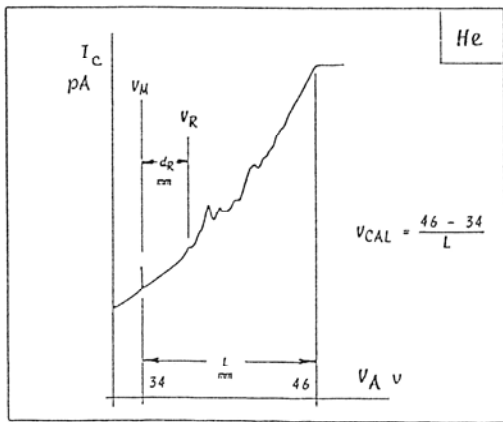


Figure 5: Scan of upper critical region (helium is on the left, neon is on the right).

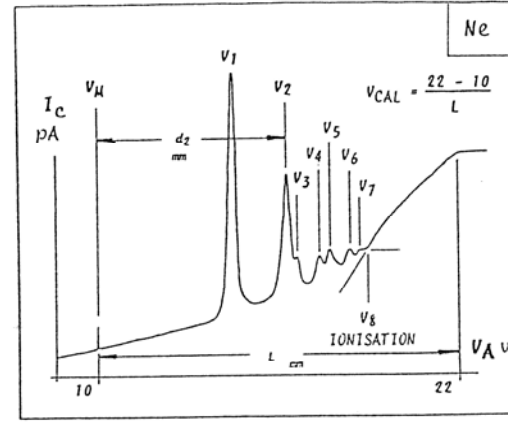
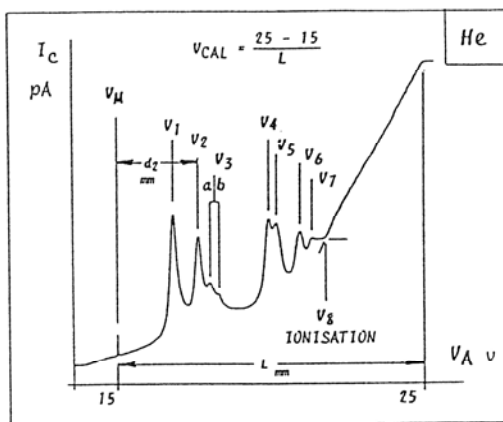


Figure 6: Scan of lower critical region (helium is on the left, neon is on the right).

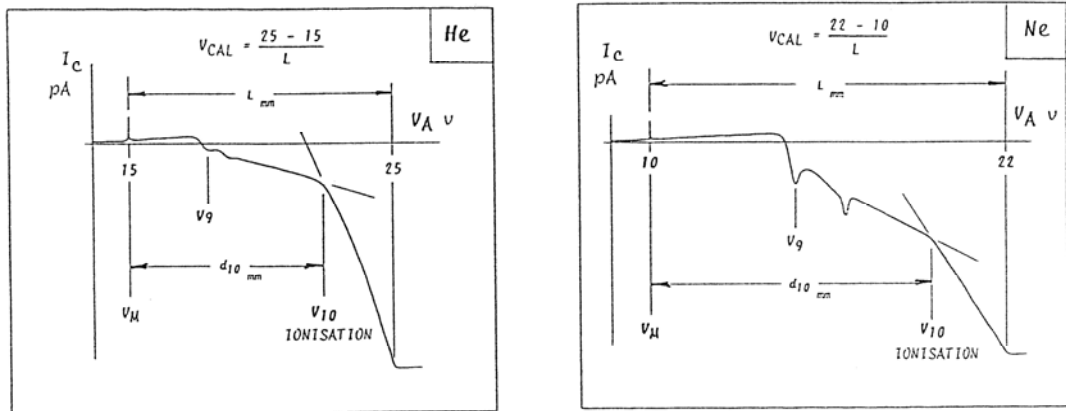


Figure 7: Ionization scan for positive ions (helium is on the left, neon is on the right).

9. When you are happy with your scan, print it out using the oscilloscope utility. **Make sure to mark on your plot which the MIN and MAX voltage were and which gas you were using. Then use the cursor utility to determine the time difference of each of your peaks relative to the start of the ramp and write it directly on your paper.** You will need this information later to analyze your data (so you can convert from time to accelerating voltage).

10. Now you will do three other types of scans for helium; the set-up steps for each one are outlined below. For each scan you need to print out channel 1 and channel 2 and do the labeling of the time difference of any peaks relative to the start of the ramp, as described in step 9. Also for each scan you may need to adjust the filament voltage to get it to look good; don't exceed filament voltage of 1.5 A or filament current of 5.0 V.

11. Scan of upper critical region: Reduce the collector voltage from 1.5 V to 0.75 volt by moving the red connector on the battery unit to the "B" output (it should currently be connected to the "-" output). Set the MIN and MAX values as shown in the left half of Figure 5. Perform the scan and print the plots. Note the MIN and MAX values on your plots, and determine the times and write down the times of any peaks you see.

12. Scan of lower critical region: Leave the battery set up as described in step 11. Set the MIN and MAX values as shown in the left half of Figure 6. Perform the scan and print the plots. Note the MIN and MAX values on your plots, and determine the times and write down the times of any peaks you see.

13. Now you will collect ionized (positive) helium or neon atoms, rather than electrons. To do this you will change the sign of the bias on the collector ring. To do this, simply reverse the 1.5 volt battery in its holder. Set the MIN and MAX limits as shown on the left half of Figure 7. Perform the scan and print the plots. Note the MIN and MAX values on your plots, and determine the times and write down the times of any peaks you see.

14. Now set the battery holder back to the way it was at the beginning – proper polarity + to + and – to – and hook the red connector up to the “-“ output. Turn off the filament power supply and replace the helium tube with the neon tube. Please ask your TA for help on this part.

15. Make the same four scans for neon. The expected neon outputs are shown in the right halves of Figures 4 -7.

16. Before leaving the lab, check with your TA to make sure you have all the plots you need and that you have labeled them with the information you need to do your report.

## Report

Your report should address all of the following points.

1. Introduction: Include a brief description of the experiment you have done and the measurements you will report.

2. Calibration: Include your oscilloscope plots that you made. For each plot, you need to determine the relation between accelerating voltage and time. You should have noted down the MIN and MAX accelerating voltages for each case; the accelerating voltage varies linearly between these values for the duration of the 40 msec ramp cycle. For each feature that you labeled with a time, you should use your calibration to convert the time to a voltage and write it on your plots. Make sure to write down a sample calculation to indicate how you perform the accelerating voltage to time calibration.

3. Broad exploratory scan (corresponds to figure 4 in the writeup): For each exploratory scan, you should see two sets of peaks. Write down what rough separation (in volts) you determined for the two sets of peaks. Explain why there is a second set of peaks and what it corresponds to.

4. Determination of  $V_0$ : As explained in the writeup, the actual kinetic energy of the accelerated electrons is given by:

$$KE = e(V_A + V_0)$$

where  $V_A$  is the anode voltage and  $V_0$  is the thermionic work function of the filament.  $eV_0$  is the amount of kinetic energy the electrons have when they leave the filament surface, before being accelerated by the anode potential. Look at Figure 4; it defines three quantities:  $V_1$  which is the anode voltage corresponding to exciting the first excited state in helium (neon),  $V_R$  which is the anode voltage corresponding to exciting the first excited state in helium (neon) in two different atoms, and the difference between these  $V_{e1}$  which corresponds to the potential of the first excited level in helium (neon). With these definitions, we have:

$$V_{e1} = V_R - V_1 = V_1 + V_0$$

$$V_0 = V_R - 2V_1$$

Use your scan of the upper critical region (the one corresponding to figure 5) to determine  $V_R$  for both helium and neon; do this by finding the feature corresponding to  $V_R$  on your plots, labeling it, and determining its voltage. Use your scan of the lower critical region (the one corresponding to figure 6) to determine  $V_1$  for both helium and neon; do this by finding the feature corresponding to  $V_1$  on your plots, labeling it, and determining its voltage. From these data determine  $V_0$  for both helium and neon.

5. Determination of excited levels in helium: From your scan of the lower critical region in helium (the one corresponding to Figure 6) you can determine the energies of several of the excited states of the helium atom. From the anode voltage for each of the peaks the energy  $E_n$  of the corresponding level in helium (relative to the ground state) is given by:

$$E_n = e(V_{An} + V_0)$$

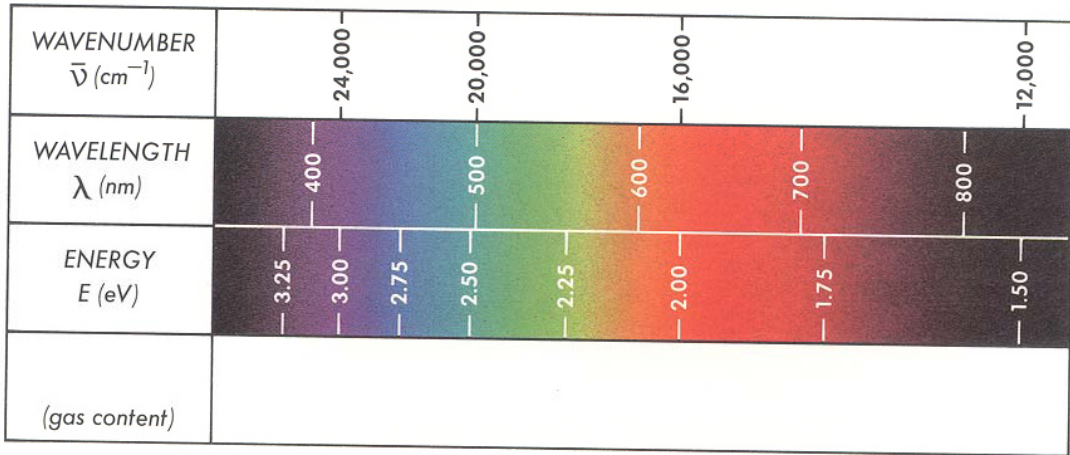
where  $V_{An}$  is the anode potential for that peak. Label each of the peaks you see in your scan using the designations given in Figure 6 for helium (you may not be able to observe all the peaks that were observed in Figure 6). Summarize your results in a table that should have your determination of the excitation energy for each peak in eV. If you did not observe a peak then simply write “not observed”. Add a column for “comparison to known values” and in that column put which of the energies from the accepted values (Table 1) that you think corresponds to what you observed. (Note: The last feature labeled as  $V_8$  corresponds to the energy needed to ionize an electron from helium).

6. Determination of excited levels in neon: Repeat the analysis described in step 5 for your neon spectrum. Prepare a table of results and comparisons for neon.

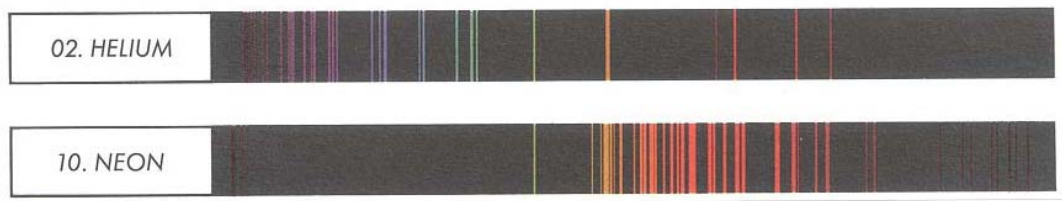
7. Determination of ionization energies: For helium and neon you took a scan where you detected positive ions (as shown in Figure 7). Production of positive ions occurs through ionization. Find the feature labeled  $V_{I0}$  in each of your positive ion plots, and use the above formula to determine the ionization energy in helium and neon.

8. Determination of possible transitions in the visible region: For the energy levels you determined in steps 5 and 6, write down the energies in eV for all possible transitions between the levels. Indicate which are in the visible spectrum (1.5 – 3.25 eV) and compute their wavelength and determine their color using the color map on the next page. Also shown on the next page is the visible spectrum for helium and neon.

9. Conclusion: Write a brief conclusion summarizing the major findings of your experiment.



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