

Critical Potentials of Helium and Neon

I. Introduction

In the previous experiment we looked at the characteristic wavelength spectra of light emitted by hydrogen and multielectron atoms. The discrete nature of these atomic emissions is a result of the energy quantization of the atomic states, and confirms the hypotheses of de Broglie and Bohr. In the more modern quantum theory, this energy quantization is required by the Schrödinger equation, an eigenvalue equation whose eigenvalues correspond to the energies of the allowed states. Another important experiment confirming the energy quantization of atomic states was performed by James Franck and Gustov Hertz in 1912. For their work they received the Nobel Prize in 1925. In this laboratory exercise we will perform an experiment similar to that performed by Franck and Hertz.

II. Theory

First lets look in detail at the experiment performed by Franck and Hertz in 1912. Consider the experimental setup shown in Figure 1.

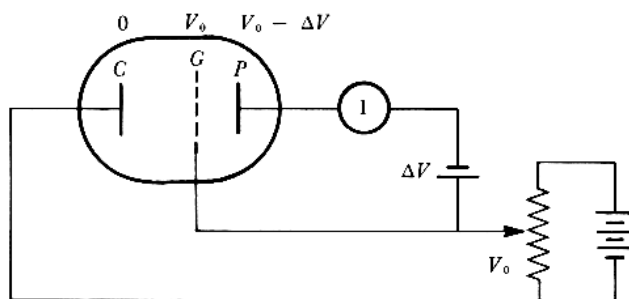


Figure 1 – The Franck-Hertz Apparatus. Electrons leave the cathode (C) and are accelerated toward the grid (G). Some pass the grid and are collected on the anode (P) (taken from Paul A. Tipler, **Modern Physics**, Worth Publishers, 1978).

In this experiment, electrons are emitted by a hot cathode into a glass chamber containing low pressure mercury (Hg) vapor. The electrons are then accelerated toward the grid which is at a potential of $+V_0$ relative to the cathode. The electrons pass through the grid, toward the anode, which is held at a potential $-\Delta V$ relative to the grid, so it tends to repel the electrons. The electrons that reach the anode are collected, and the current reaching the anode can be measured as a function of V_0 . The results obtained by Franck and Hertz are plotted in Figure 2.

As can be observed, the current reaches a maximum at about 4.9 V, then decreases, only to reach a second maximum at twice 4.9 V and a third maximum at three times 4.9 V. Now consider the energy level diagram for Hg, shown in Figure 3.

The mercury atom has atomic levels similar to those of helium, since it has a series of closed inner shells out to $5s^2p^6d^{10}$ and 2 outer electrons in the 6s shell, just like helium with its $1s^2$ configuration. These two outer electrons each have spin $\frac{1}{2}$, so they can be in a total spin $S = 0$ state (“para-mercury”) when the spins are oppositely aligned, or in a total spin $S = 1$ state (“ortho-mercury”) when they are parallel. The total angular momentum quantum number J given by $J = |L - S| \dots L + S$.

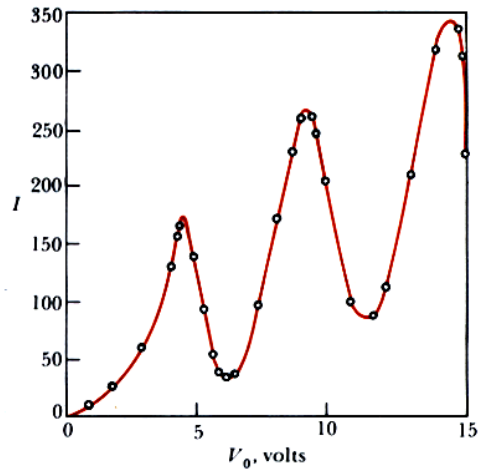


Figure 2 – A plot of the anode current as a function of accelerating potential V_0 for the Frank-Hertz experiment (taken from Paul A. Tipler, **Modern Physics**, Worth Publishers, 1978).

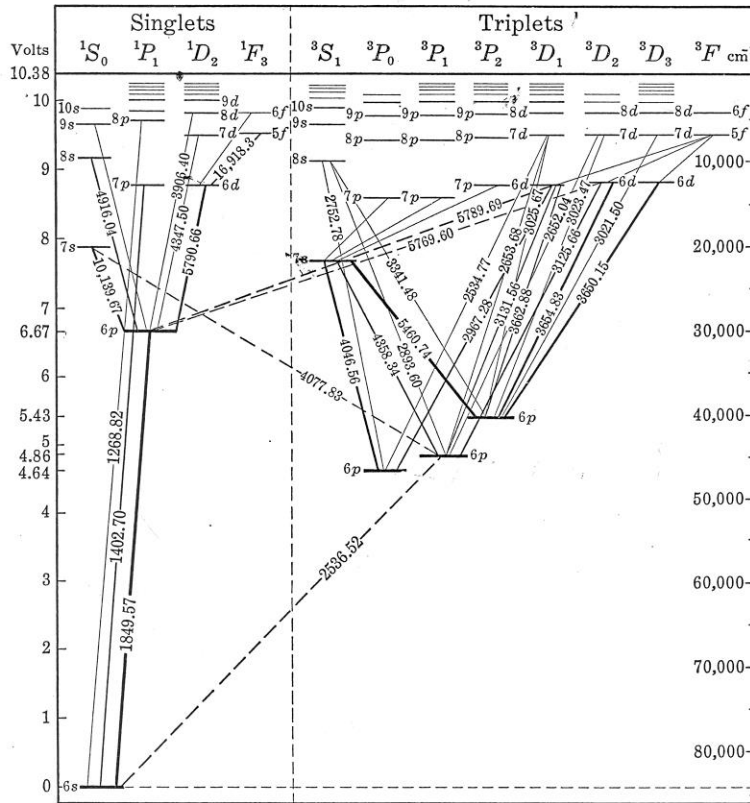


Figure 3 – The energy level diagram for Hg. The outer electron configuration of mercury is very similar to helium, since it has an electron configuration $1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^{10} 4p^6 5s^2 4d^{10} 5p^6 6s^2$ and helium has $1s^2$. The spectroscopic notation for the states is $^{2S+1}L_J$.

This gives

$$\begin{aligned}
 J &= L && \text{for } S = 0, \text{ and} \\
 J &= L - 1, L, L + 1 && \text{for } S = 1.
 \end{aligned}$$

Here the state $S = 0$ state is called the “singlet” because there is only one allowed value of J for each value of L . The $S = 1$ state is called the “triplet” state, since there are three allowed values of J . This is shown in the spectroscopic notations at the top of Figure 3.

The explanation for the results of the Franck Hertz experiment is then clear; we see that the electrons when they reach the grid with energy of at least 4.9 eV can excite the first excited state of the Hg atom at about 4.9 eV. As long as their energy was below 4.9 eV, the electrons could only have elastic collisions with the mercury atoms, therefore did not lose very much energy and they could easily overcome the small potential ΔV to reach the anode. At energies above 4.9 eV, however, the electrons could transfer 4.9 eV of their energy to excite the first state of Hg in an inelastic collision. These electrons are left with very little kinetic energy, and are therefore unable to reach the anode. Hence, the current drops drastically after 4.9 eV.

If the electron has 9.8 eV it can excite electrons from two Hg atoms into the first excited state, so we would expect another sharp drop in current. Similarly, at 14.7 eV, three electrons can be promoted, and so forth.

What about the other excited states besides 4.9 eV? The 3P_0 and 3P_2 states cannot de-excite (the transition is forbidden by the $\Delta J = \pm 1$ selection rule) so these are metastable states – once they are excited they cannot de-excite and absorb more energy. The 1P_1 state requires significantly more energy (6.7 eV) to excite than the 3P_1 state, and so it is not observed – all of the energy is effectively transferred once the electrons reach 4.9 eV.

Also notice from Figure 3 that the ionization energy for Hg is about 10.5 eV (actually 10.38 eV). This is the energy required to completely remove the first electron from the Hg atom.

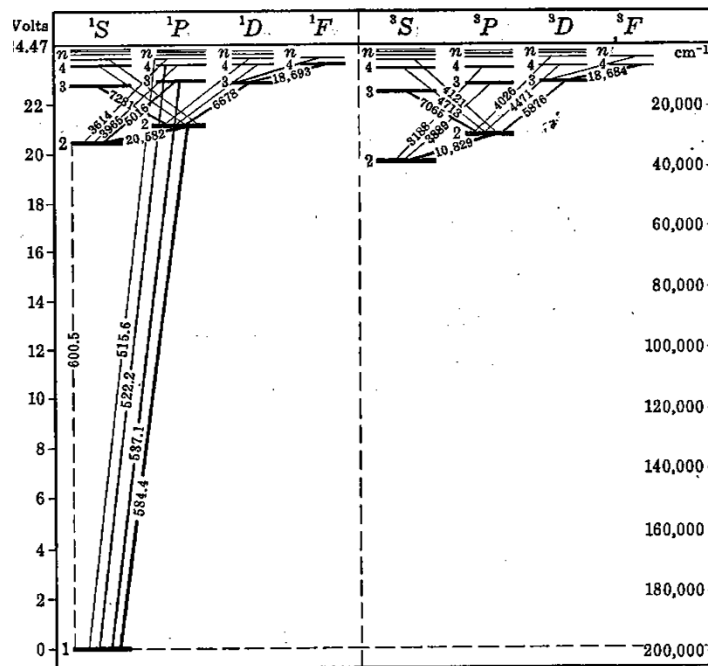


Figure 4 -- The energy level diagram for helium showing the singlet and triplet states. Notice the similarity to the Hg energy level diagram in Figure 3.

In our experiment, we plan to examine this same effect in He and Ne gases rather than in Hg. An examination of the energy level diagram for helium (Figure 4) shows that it is very similar to Hg. Helium has both singlet and triplet states, although in Figure 4 the complete spectroscopic notation is not given, and the triplets are shown as a single state, e.g. the state labeled 3P for orthohelium ($S = 1$) is really 3P_0 , 3P_1 , and 3P_2 . Interestingly, the

selection rules are $\Delta S = 0$, $\Delta L = \pm 1$, and $\Delta J = 0, \pm 1$ but not $J = 0$ to $J = 0$, so that it is difficult to excite the orthohelium states directly from the ground state.

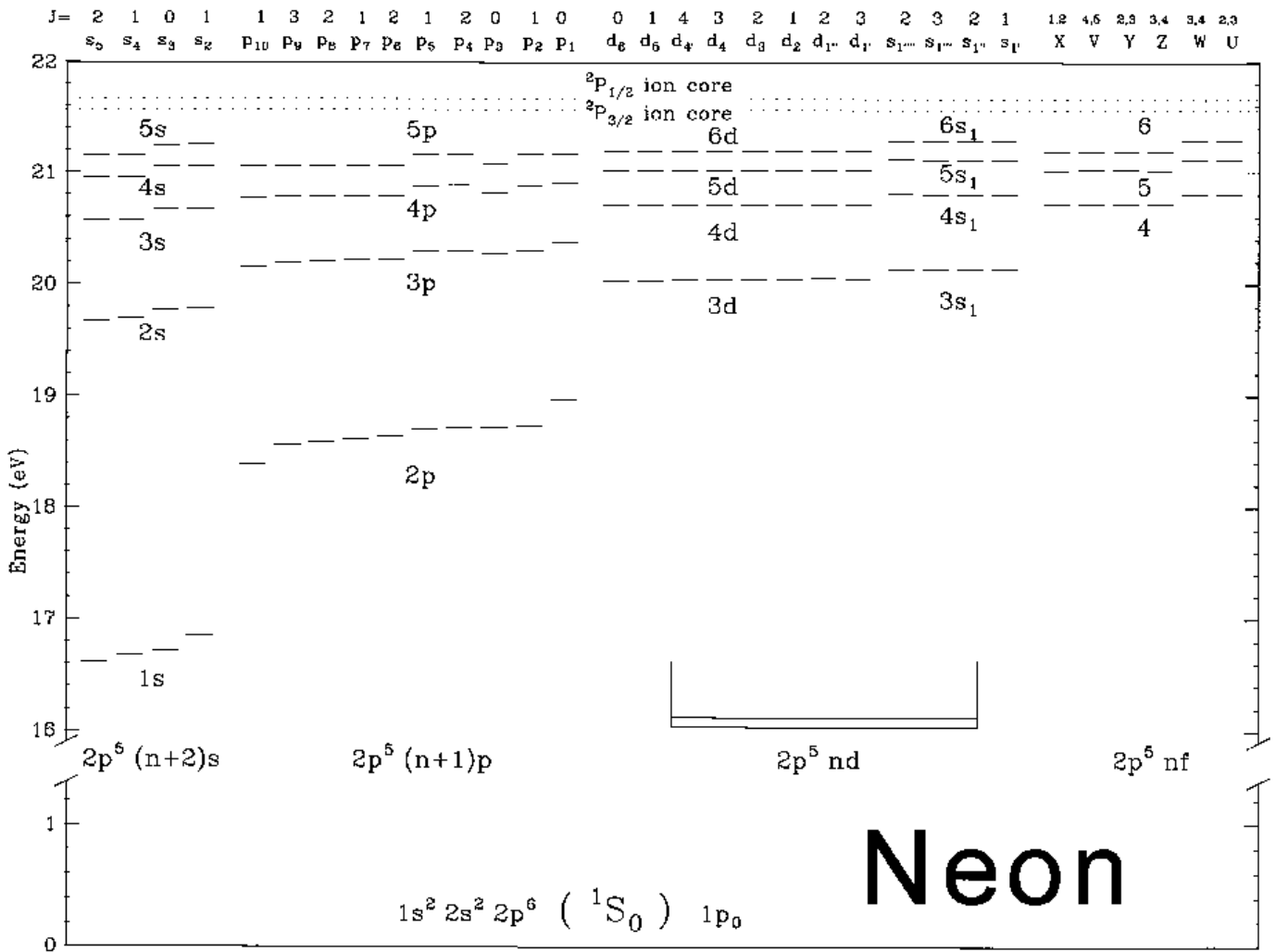


Figure 5 – The energy level diagram for neon. The outer electron configuration for neon is different than He or Hg; it is $1s^2 2s^2 2p^6$.

In Figure 5 we see the energy levels for neon. Since the electron configuration of neon is quite different, $1s^2 2s^2 2p^6$, the energy level diagram is also dissimilar. Nevertheless, distinct energy levels can be seen which depend on the principle quantum number and the orbital angular momentum.

III. Experimental Apparatus

The electronic schematic for our experiment is shown in Figure 6. The most important component in this experiment is the TEL 2533 critical potentials tube (see Appendix A). This tube comes filled with either low-pressure helium (TEL 2533/02) or neon (TEL2533/10).

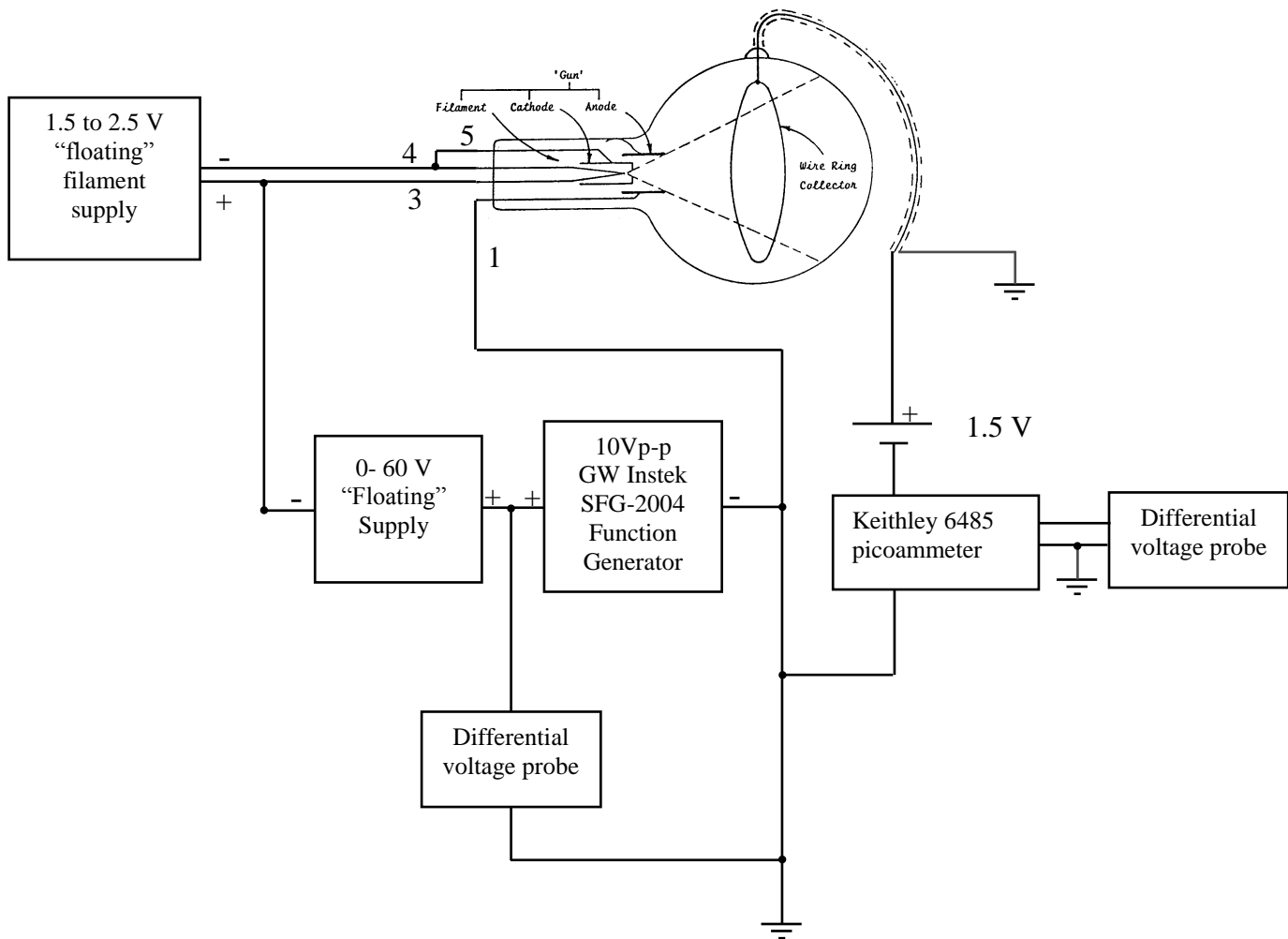


Figure 6 – The electronics schematic for the experiment. A function generator provides a varying accelerating voltage to the TEL 2533 tube. The TEL 2533/02 tube is filled with low-pressure helium, while the TEL 2533/10 tube contains neon. The current is monitored with the Kiethley picoammeter and read into the computer along with the accelerating voltage using the Vernier differential voltage probe.

A voltage of between 1.5 and 2.5 V is required to heat the filament, which then releases electrons. The electrons are accelerated by the potential placed on the anode. This voltage is supplied by the “floating” 0-60V power supply and the function generator. The 0-60V range is obtained by using both floating outputs of a dual power supply in series. Using the function generator, the voltage can be automatically varied over a -5 to 5 V range around the value given by the 0-60 V power supply. This voltage is monitored using the Vernier voltage probe.

The electrons are accelerated by the potential on the anode. After they pass the anode, they continue out into the tube, eventually striking the wall on the far side and being collected. The glass tube is coated with a conductive material that is electrically connected to the anode. However, if the electrons lose energy by an inelastic collision with an atom, then they will be attracted to the positive potential (supplied by a 1.5 V battery) on the collecting ring. The electrons are collected and their current measured by the Keithley picoammeter. This electrometer produces an output voltage proportional to the current, which is monitored by the Vernier instrumentation amplifier.

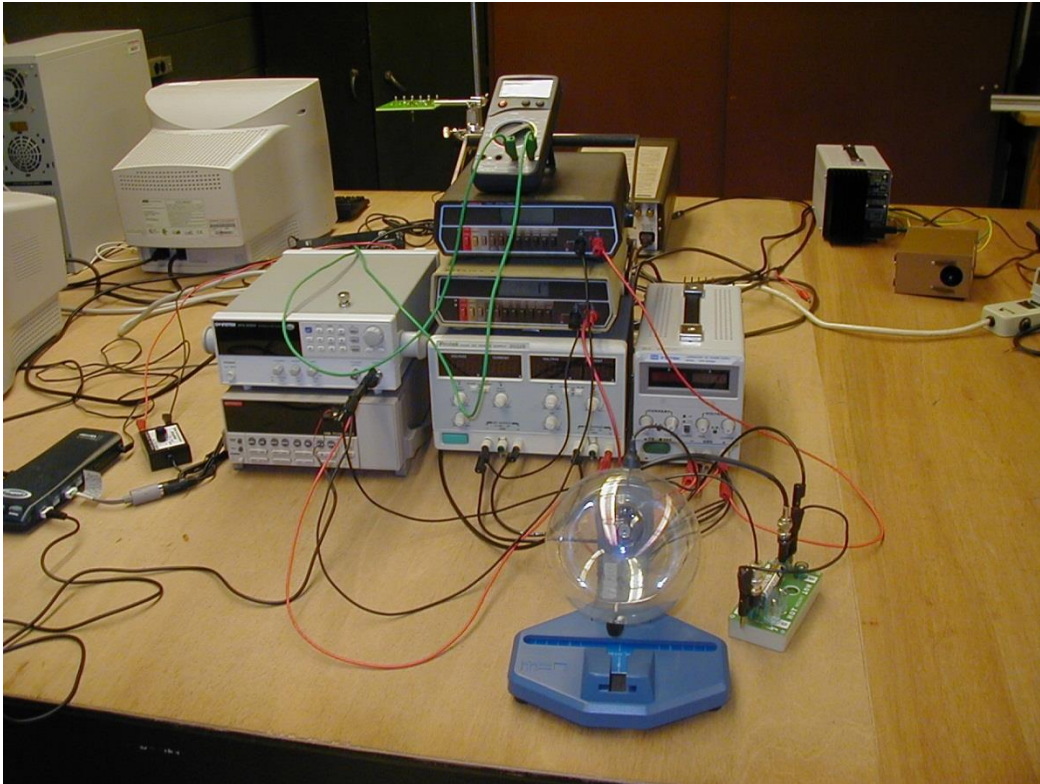


Figure 7 – A photograph of the experimental apparatus. From left to right are the computer (not visible), the Vernier Labpro and instrumentation amplifier, the function generator (top) and picoammeter (bottom) used to monitor the accelerating voltage and current, the power supplies for the accelerating potential (bottom left) and filament (bottom right), and some multimeters (on top) to monitor the voltages. The TEL 2533 critical potentials tube (front), and battery holder.

IV. Experimental Procedure

This is just a rough suggestion of how to proceed. Please carefully consider for yourself how this measurement would best be made.

- A. Carefully examine the apparatus to assure it is set up correctly. **Begin with the helium tube (TEL2533/02)**. Record in your logbook the circuit you are using. Do not assume you will find it in working order, or that it will be the same as Figure 6.
- B. **Before turning anything on, make sure all the voltages are turned down.** It is very easy to destroy the filament by using too high a potential. These tubes are quite expensive.
- C. Turn on the power supply, and turn up the filament voltage to about 2 V. You should be able to see it glowing. **DO NOT GO OVER 2.5V OR YOU WILL DESTROY THE TUBE LIKE I DID!** These tubes are very expensive.
- D. Turn on the function generator and adjust it so that the accelerating potential scans from about 15 V to about 25 V over the longest time period possible.
- E. Turn on the picoammeter. Adjust the scale to give a mid-scale reading. You can easily affect the reading by touching wires and etc. so be careful when taking data.
- F. Start LoggerPro and set it up for the voltage probe and instrumentation amplifier. You may want to set up a column with the smooth function.

- G. Make a column that shows the correct accelerating voltage (i.e. the sum of the power supply and the function generator).
- H. Set the Logger Pro trigger to begin data collection at the lowest voltage and to collect for one-half cycle. The results should look something like Figure 8.
- I. Try adjusting the filament voltage in the range 1.5- 2.5 V to obtain the best results.
- J. Repeat the scan for accelerating voltages in the range 34 to 46 V.
- K. Turn down all of the voltages and replace the helium tube with the neon tube (TEL 2533/10).
- L. Repeat steps A through J, but in this case make the low energy scan from 12 V to 20 V and the higher energy scan from 28 V to 38 V.

V. Experimental Results

At this point you should have four scans – a high and low energy scan on helium and on neon. Start by examining the helium:

- A. Determine the energies of the peaks in the low energy scan. Can you draw any conclusions by comparing them with the helium energy level diagram?
- B. Locate the ionization potential (24.6 eV) on the scan. Is there any feature present? Can you explain what is happening?
- C. Examine the high-energy scan. Are there peaks present? How can they be present for voltages above the ionization potential?
- D. Determine the energies of the peaks in the high energy scan, if they are present. Can you identify the causes of these peaks?
- E. Compare your results with Figure 9 and Figure 10, which show the scans obtained by the tube manufacturer. Can you think of any reasons for the difference?

Now look at the neon scans:

- F. Determine the energies of the peaks in the low energy scan. Can you draw any conclusions by comparing them with the helium energy level diagram?
- G. From the energy level diagram, determine approximately the ionization potential. Locate the ionization potential on the scan. Is there any feature present? Can you explain what is happening?
- H. Examine the high-energy scan. Are there peaks present? How can they be present for voltages above the ionization potential?
- I. Determine the energies of the peaks in the high energy scan, if they are present. Can you identify the causes of these peaks?
- J. Compare your results with Figure 9 and Figure 10, which show the scans obtained by the tube manufacturer. Can you think of any reasons for the difference?

VI. Questions to Ponder

Here are some additional things to think about or to try. Be sure to put your thoughts and results in your logbook.

- A. Why do we use a 1.5 V battery? Would a power supply work? Would a different voltage work better than 1.5 V?
- B. Why are the electronics set up in such a crazy way? Why is the common ground where it is?
- C. What is the uncertainty in the measured accelerating voltage? In the current? Is there any way to reduce these uncertainties?
- D. Is there any way you can think of to improve the resolution (i.e. make the peaks sharper, like in Figure 9 and Figure 10).
- E. Why do we only see some of the energy levels and not others?
- F. What would you expect to see at even higher potentials?
- G. What is the He and Ne pressure in the tubes? What effect does the pressure have on this measurement?

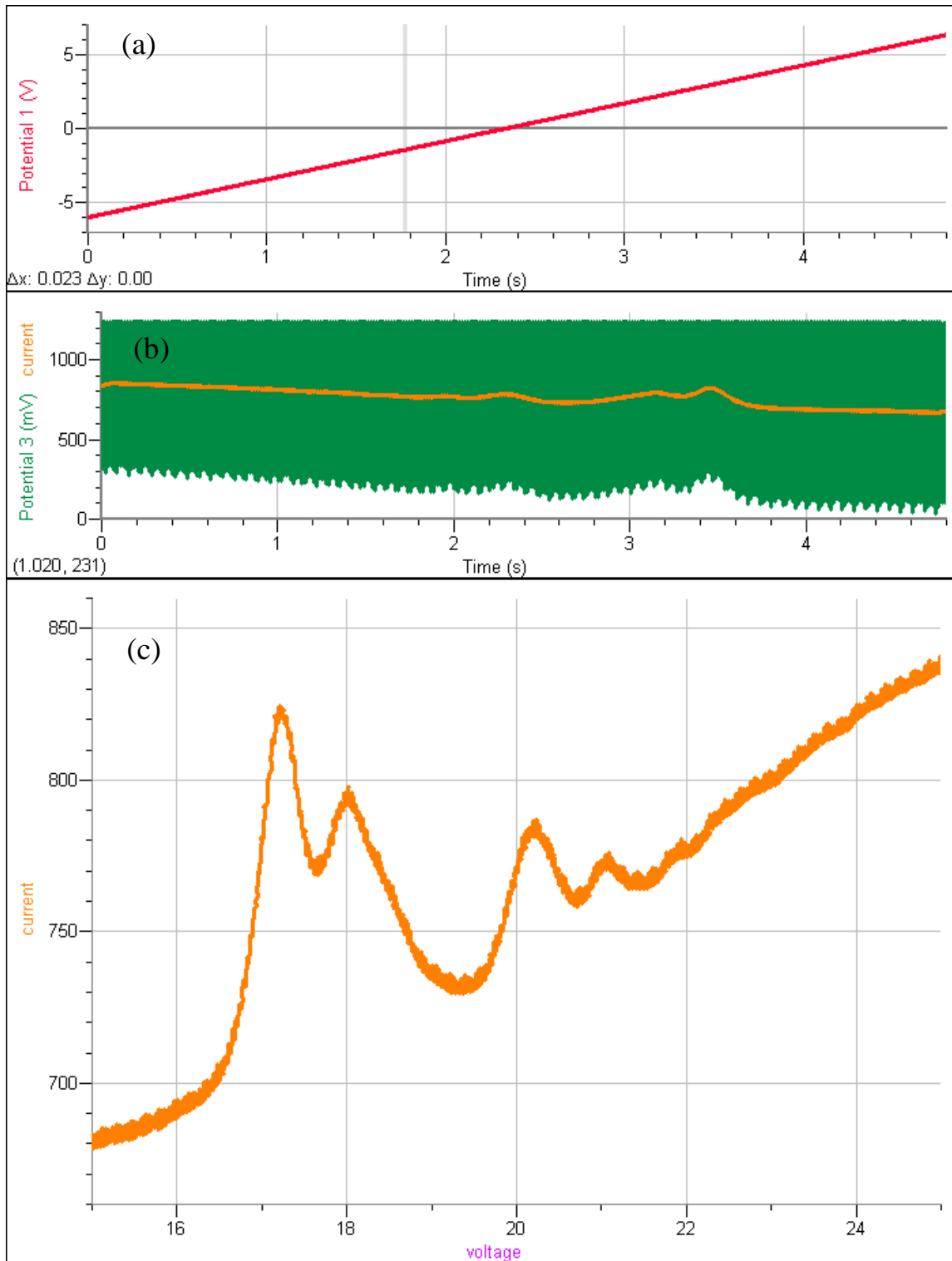


Figure 8 – (a) The potential across the function generator. The sum of this potential and the potential across the 0-60 V power supply is the accelerating potential. (b) The voltage output by the picoammeter, which is proportional to the current. It has not been calibrated. The raw data are green, the smoothed is orange. (c) An uncalibrated scan of the current as a function of accelerating potential from approximately 15 to 25 V for the helium tube. One thousand points were collected per second, with averaging over 97 points. Several peaks in the current are evident.

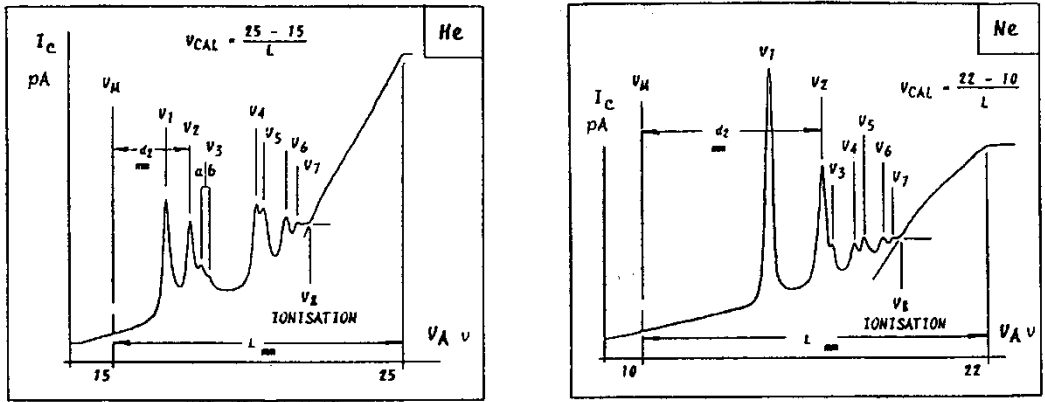


Figure 9 – A plot of current versus accelerating voltage for the low-energy scan, as provided by Tel-Atomic, the manufacturer of the TEL 2533/02 critical potentials tube.

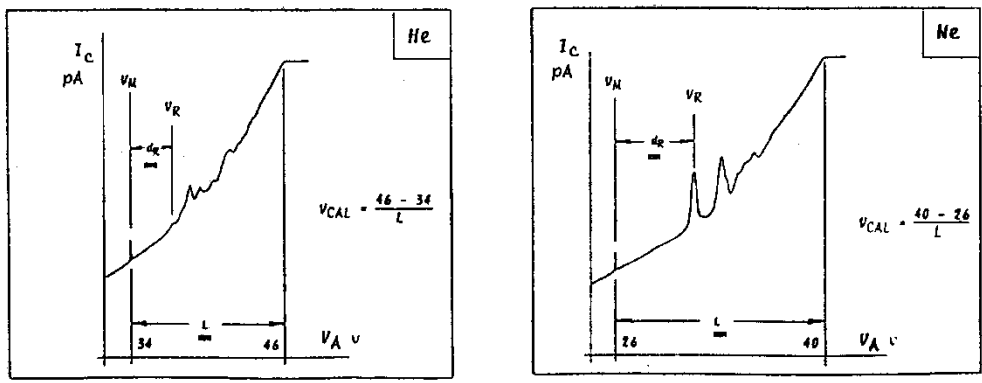
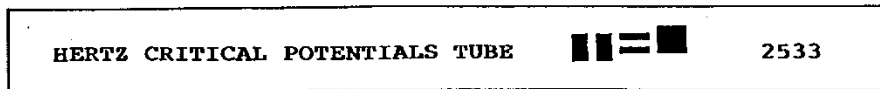


Figure 10 -- A plot of current versus accelerating voltage for the low-energy scan, as provided by Tel-Atomic, the manufacturer of the TEL 2533/02 critical potentials tube.

Appendix A

1



THE HERTZ CRITICAL POTENTIALS TUBE, TEL.2533 comprises a 'cathode ray gun' which projects a divergent beam of electrons into a clear glass bulb which contains gas at low pressure; the gas in 2533/02 is Helium and in 2533/10 is Neon. Located inside the bulb is a wire ring collector electrode so positioned that it cannot receive electrons directly from the source of the beam; the ring is connected to a screened lead terminated with a BNC plug. The source of the beam is a tungsten 'hairpin' filament connected to Pins 3 and 4 and housed within a cathode can which is connected to Pin 5. The anode cylinder of the 'gun' has an external connection at Pin 1. The inside surface of the glass bulb is coated with a transparent conducting layer; this coating is insulated from the wire ring but connected internally to the anode cylinder.

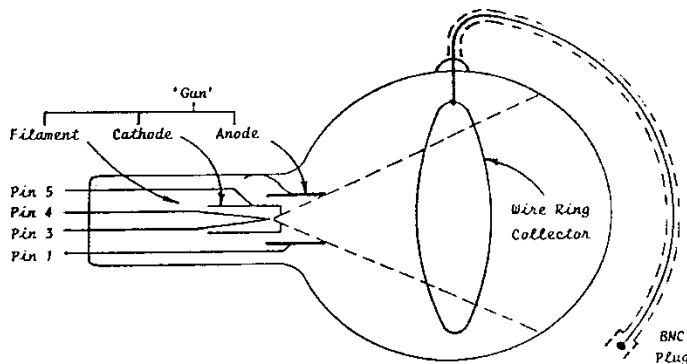


FIGURE 01 : SCHEMATIC OF THE HERTZ CRITICAL POTENTIALS TUBE , TEL.2533

Specification:

FILAMENT VOLTAGE (V_F)	...	3.0 V dc max.
ANODE VOLTAGE (V_A)	...	0 - 50 V dc (60 V max)
ANODE CURRENT (I_A)	...	10 mA max.
COLLECTOR VOLTAGE (V_C)	...	± 1.5 V dc, dry cell battery, type AA (HP7).
COLLECTOR CURRENT (I_C)	...	0 to ± 200 picoamps.

The tube is mounted in the UNIVERSAL STAND, TEL.2501.