INTRODUCTION

Early spectroscopic experiments demonstrated that atoms emit and absorb electromagnetic radiation at discrete frequencies, confirming Bohr’s hypothesis of energy quantization. The frequency ν of the radiation emitted or absorbed is related to the change in energy levels of the emitting atom. That is, $hν = ΔE$, where $h$ is Planck’s constant and $ΔE$ is the difference in energies of two atomic states. Appendix II shows examples of discrete energy levels in an atom.

In 1914, James Franck and Gustav Ludwig Hertz started a series of experiments to investigate the ability of an atom to absorb kinetic energy of a bombarding electron. The results of earlier spectroscopic experiments implied that the kinetic energy of an electron can also be transferred to an atom only in discrete amounts corresponding to the difference in energy levels of the atom. Franck and Hertz demonstrated that:

- it is possible to excite atoms by bombardment with low energy electrons,
- energy is transferred from the electron to the atom in discrete amounts, and
- the energy level differences deduced are in agreement with spectroscopic results (of the sort that we find in the ‘Atomic Spectra’ Lab).

Franck and Hertz shared the 1925 Nobel Prize “for their discovery of the laws governing the impact of an electron upon an atom”. The physics and description of the experiment are likely to appear in your Physics 284 textbook.

OVERVIEW of the EXPERIMENT

The present experiment closely follows the classic Franck-Hertz experiment. In part A, the apparatus consists of a glass envelope containing mercury vapor and kept at a temperature of 195 °C in an oven. A current heats the filament. Electrons from the filament are accelerated by the potential $V_A$ toward a grid. If the electrons have lost no energy in collisions with mercury atoms between the filament and the grid, they will have enough energy to reach the collecting anode (called the plate), in spite of the small retarding potential $V_R$. The current due to electrons reaching the plate is measured by the ammeter A. (In our experiment we might use a very sensitive electrometer, capable of measuring picoamps.) This current rises as the accelerating potential $V_A$ is increased from zero.
When $V_A$ is equal to or slightly greater than the minimum excitation potential of mercury atoms, electrons can make inelastic collisions: they transfer some of their energy to the mercury atoms. The electrons that have experienced an inelastic collision do not have enough energy remaining to reach the plate in the presence of the retarding voltage. Hence the current decreases. When the accelerating potential is further increased, these electrons have enough energy to reach the plate, and the current will increase again.

When an atom returns from the excited state to the ground state, a photon is emitted and the gas glows at the wavelength or frequency $\nu$ corresponding to the transition energy. Hence the response of the current is related to the color and intensity of the glow.

When $V_A$ is large enough for a single electron to excite two atoms in successive collisions, there will be a second decrease in the current. Thus, if we plot the plate current as a function of the accelerating voltage, we expect a series of equally spaced current dips, corresponding to excitations of mercury atoms. The dips are not sharp, and do not go to zero because of several factors. (For instance, electrons are emitted from the hot filament with a distribution of energies.

**A NOTE on UNITS: The ELECTRON-VOLT (eV)**

In an electric field, an electron accelerates and gains kinetic energy. If it moves through a distance that corresponds to a voltage change of $\Delta V$, then its increase in kinetic energy equals the loss of potential energy: $\Delta E = e \Delta V$ ($e$ is the electron’s charge). This has led to a standard unit of energy: the ‘electron-volt,’ eV. It is the kinetic energy of an electron that has been accelerated by 1 Volt. When you set $V_A = 40V$, you obtain electrons with 40 eV of kinetic energy.

**PROCEDURE**

There are two parts to the experiment. Part A is with a mercury-filled tube in an oven, and Part B is with a room temperature tube containing mercury and neon. The description above applies directly to Part A. In this case, we cannot observe the light emitted as the atoms return to the ground state, but we can observe the changes in electron current, and measure the excitation energy.

The physics of Part B is the same as part A. However, this is set up so that we can observe the light emitted as the atoms return to the ground state. On the other hand, we will not be able to measure multiple cycles of the electron current. The wavelengths observed will be compared to the full spectrum observed in Hg and Ne gas discharges.

The two parts of this experiment may be performed in either order, and there is only one apparatus for each part. You will have to switch midway through the lab period.
The filaments of these tubes are very fragile, and the tubes are expensive. Do not turn on the filament supply, or change the filament current, until the instructor has verified that you understand the current controls.

Under no circumstances should you exceed the posted maximum filament current, and the current should not be changed abruptly. The maximum filament currents are posted in the lab.

PART A (mercury filled tube in oven)

Check with the instructor before turning on power to the apparatus.

An oven temperature of 195 °C is recommended to keep the Hg vapor at the optimum vapor pressure for electron-gas collisions. The oven will be on before you arrive, so there is no need to adjust the rheostat that is connected to the oven.

• First, understand the sequence of actions to be performed to get the apparatus to measure the voltage and current with the help of the instructor. The basic approach is that the current response can be observed and measured approximately on the oscilloscope, but accurate measurements should be made with the electrometer.
• One way of observing the current dips is to ramp the accelerating voltage periodically and observe the plate current response on the oscilloscope. (The device can do this with the ‘ramp’ setting.) Study the oscilloscope traces (x-y mode, showing the accelerating voltage and the plate current). Look at this trace with care. Based on this, select a series of accelerating voltages near which to make precise measurements of the anode current. The goal is to measure accurately the voltages corresponding to dips in the current.
• Now use the current amplifier inside the electronic box to make more precise measurements. In the region of each current dip, make several measurements of current vs. voltage. You should look at 3 or more dips accurately so that you have at least 2 measurements of the voltage difference.
• As you collect data, plot a graph of the current as a function of voltage. Verify that the dips in the current can be seen. (But recall that you only need the data near the dips, not at the peaks.) It is not sufficient to measure the voltage for each dip simply using the knob; you need to plot several current & voltage values for each dip.

PART B (tube containing both mercury and neon at room temperature)

Check with the instructor before changing filament current or turning on power to other parts of the apparatus.

• As you ramp up the voltage, take note of the behavior of the current.
• Determine the onset voltages for the Hg glow, and then for the Ne glow. Make small voltage increments in the region where the Hg and Ne radiation starts to glow.
The experiment is set up with a diffraction grating spectrometer and two gas discharge tubes (one filled with Ne, one with Hg). The spectrometer enables you to see the separate spectral lines. This will be a great help in identifying which atom is responsible for which color. First try comparing the colors in the Franck-Hertz tube to the reference discharge tubes provided for your use. Then try to use the spectrometer to prove which color corresponds to which gas. Appendix III describes the basic operation of the spectrometer.

A plot of the expected voltage vs. current behavior and the main energy levels and spectral lines of mercury and neon are shown in Appendices I and II.

DATA ANALYSIS

PART A
Plot the accelerating voltage vs. plate current and make a table of the voltages at which there are minima in the current. Then, make a table of the voltage differences of successive current minima.

Using the above table, what is your best value for the energy level difference observed in mercury? What wavelength of light would be associated with this energy? Could you see this light with the naked eye?

PART B
Make a list of the currents and voltages for this tube and label points at which the blue mercury and the red and yellow neon spectral lines are observed to turn on or off. It might also help to make a rough plot.

While you might only obtain a rough idea of the behavior of the current vs. voltage, (unlike Part A), it is interesting that current starts to drop sharply at some point between 15 and 20 V in the accelerating voltage. What causes this? What other observations are linked to it? Once the current starts dropping, you have to increase the current still further to observe the red neon glow. Why is this?

In your lab report, describe the physical process taking place at each accelerating voltage where you can turn a spectral line on and off, i.e. which energy levels (specify the voltage) are being excited and which transitions are relevant. Make as close a connection as you can to the energy levels of Hg and Ne described in Appendix II.
Appendix I

Experimental Results

The following phenomena are observed visually, spectroscopically and electrically when the accelerating voltage is slowly increased commencing from 0 Volts:

1. Anode voltage range 0 to 7 V. No gas glow discernible in the discharge space, not even in total darkness. Collector electrode current smaller than \(10^{-6}\) A.

2. Anode voltage about 10 V. Faint blue glow of the mercury vapour in the vicinity of the cathode. The 434.7 and 436.8 nm wavelength mercury lines can be recognized with the spectroscope. The collector electrode current increases with further increase of the accelerating voltage. A maximum is obtained for about 17 V.

3. At 17 V marked drop of the collector electrode current, whereby the blue mercury vapour discharge glow persists. The current drop is produced by excitation of the ultra-violet neon lines at 73.5 and 74.3 nm wavelengths. The red neon lines at 640.2 and 671.7 nm wavelength appear for the first time when the anode voltage is 18.3 V. The blue glow disappears almost completely.

4. The yellow neon line at 589.2 nm wavelength appears when the voltage is increased still further. The colour of the gas discharge changes from dark red to yellowish-red. The collector electrode current goes through a minimum.

5. Yet further increase of the anode voltage leads to renewed increase of the collector electrode current up to a maximum at 21.5 V (ionization voltage of neon). After passing through a minimum at about 22.5 V, the collector electrode current rises once again. The discharge is now buffered so strongly by space charge that no further maxima or minima are produced.

Collector electrode current as a function of accelerating voltage for a mercury-neon gas mixture at room temperature
Appendix II

Simplified diagram of quantum energy levels of mercury and neon, showing the relevant transitions. Wavelengths (4 digit numbers) are specified in Angstroms ($10^{-10}$ m). The fractional numbers between 0 and 20 are the energies (with respect to the ground state) of the excited levels in units of eV.
Appendix III

Basic Operation of the Diffraction Grating Spectrometer

1. Locate the parts of the spectroscope shown in the figure. **CAUTION: Do not touch the delicate diffraction grating.** It consists of a thin layer of plastic that has been laid down upon a finely ruled steel master grating and later stripped off. The surface can easily be damaged. The diffraction grating has been accurately placed perpendicular to the axis of the collimator. The slit is located at the focal point of the collimator lens so that parallel rays, and hence plane waves, are incident upon the diffraction grating.

2. Focus the telescope eyepiece on the crosshairs by reflecting light into the telescope with white paper.

3. Place the stand containing the mercury discharge tube in front of the collimator, and just outside the collimator slit. Connect the leads from the tube holder terminals to the high-voltage power supply. **CAUTIONS:** Do not touch other apparatus when turning the power supply switch on or off. The supply provides 10,000 volts. This can be dangerous. Also do not touch the discharge tube or the high voltage wires while the current is on. Another cautionary note: the glass discharge tube cover is very hot.

4. Turn on the power supply and observe the central image produced by the diffraction grating by moving the telescope by its mounting pillar after loosening the lock nut. For fine adjustment, tighten the lock nut and use the fine adjustment knob. Carefully move the discharge tube to obtain the brightest image. **You are now ready to carry out Part A.**