ATOMIC EXCITATION POTENTIALS

PURPOSE

In this lab you will study the excitation of mercury atoms by colliding electrons with the atoms, and confirm that this excitation requires a specific quantity of energy.

THEORY

In general, atoms of an element can exist in a number of either excited or ionized states, or the ground state. This lab will focus on electron collisions in which a free electron gives up just the amount of kinetic energy required to excite a ground state mercury atom into its first excited state. However, it is important to consider all other processes which constantly change the energy states of the atoms. An atom in the ground state may absorb a photon of energy exactly equal to the energy difference between the ground state and some excited state, whereas another atom may collide with an electron and absorb some fraction of the electron's kinetic energy which is the amount needed to put *that* atom in some excited state (collisional excitation). Each atom in an excited state then spontaneously emits a photon and drops from a higher excited state to a lower one (or to the ground state). Another possibility is that an atom may collide with an electron which carries away kinetic energy equal to the atomic excitation energy so that the atom ends up in, say, the ground state (collisional deexcitation). Lastly, an atom can be placed into an ionized state (one or more of its electrons stripped away) if the collision transfers energy greater than the ionization potential of the atom. Likewise an ionized atom can capture a free electron. All these events occur at different rates, depending in part on the conditions of the gas. Figure 1 shows the energy levels for one element (mercury).

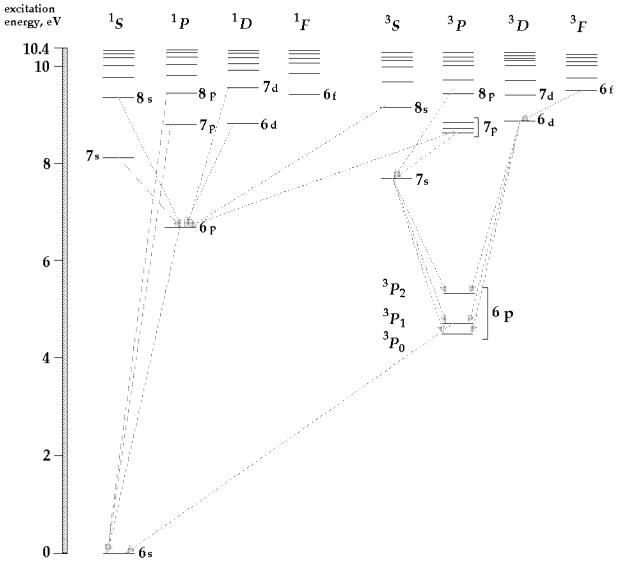

Figure 1. Mercury energy level diagram

Franck and Hertz devised an arrangement which very neatly measures the first excitation potential of mercury by amplifying the effects of collisional excitation by electrons with various energies. To see how this is done, consider the 3-element tube in Figure 2. You will heat the cathode by applying a voltage to it, and cause electrons to accelerate by applying a potential difference V between the cathode and the perforated anode. The tube is filled with mercury vapor so that collisions between electrons and mercury atoms can take place. Most of the electrons, whether they make a collision or not, will be drawn to the perforated anode and return to the power supply. Some will continue to the collector electrode which is held at a small retarding potential ΔV (one or two volts negative compared with the anode). This retarding potential limits the number of electrons reaching the collector (how?). These electrons then travel from the electrode to a current amplifier or electrometer.

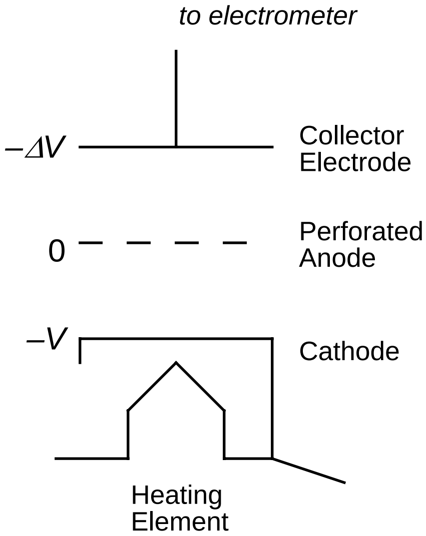

Figure 2. Franck-Hertz tube

Now consider the collisions. If the potential difference between cathode and perforated anode gives the electrons less than the energy needed to collisionally excite a mercury atom, only elastic collisions will occur. However, suppose you increase the potential so that it gives each electron just enough kinetic energy to excite a mercury atom to the first excited state. Some of the electrons will actually collide with an atom. If the remaining kinetic energy of a colliding electron is insufficient to overcome the retarding potential, such an electron will not reach the collecting electrode. Let's quantify this a little. The required excitation energy can be written in terms of the electric potential through which the electron accelerates: $E_{\mathrm{ex}} = \mathrm{e}V_{\mathrm{ex}}$ where \$e\$ is the electron charge. If the accelerating potential V has a value between V_{ex} and $V_{\mathrm{ex}}+\Delta V$, electrons which cause an excitation will not reach the collector unless they gain energy from a subsequent collision. As *V*. is increased above $V_{ex}+\Delta V$, electrons will again reach the collector electrode in greater numbers.

If one were to measure the current from the electrode as a function of accelerating potential, therefore, one would expect to obtain something like Figure 3. The separation of minima should be equal to the excitation potential (why?).

Note that if *V*. increases above the ionization potential V_{ion}, as it will in your experiment, ionization will occur, drawing a huge number of electrons to the anode and causing a large current to flow toward the power supply. You will prevent this from damaging the apparatus by connecting a relatively large resistor between anode and power supply. This current surge due to ionization will increase the potential across the resistor (consider Ohm's law) thus reducing the anode potential to a point which stops the ionization. In practice, the ionization only barely gets started.

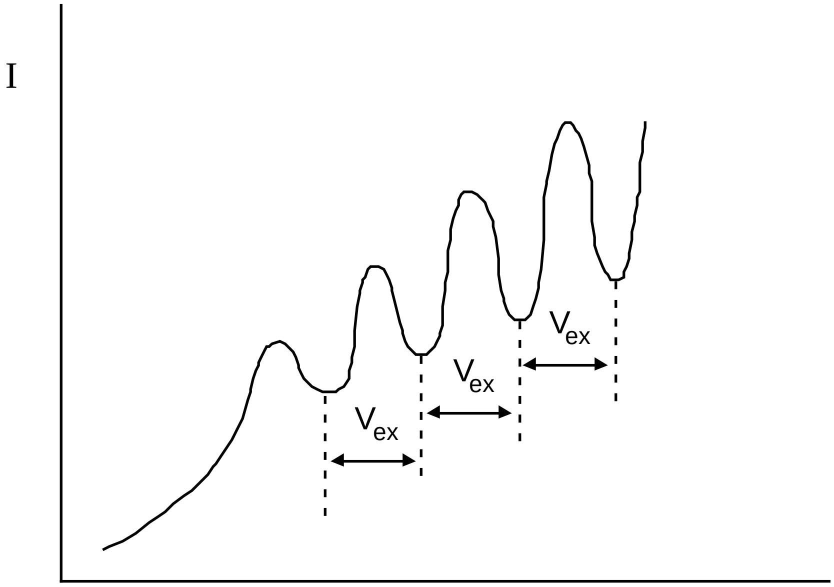

Figure 3. Current as a function of accelerating potential

PRELAB

1. Roughly sketch equipotential lines for the portion of the tube between cathode and anode. Choose a potential *V*. which is 3.5 times the first excitation potential of mercury. Indicate on the sketch the locations at which you expect the most excitations to occur (note that, and explain why, each electron can cause up to 3 excitations). You will try to observe this (qualitatively) in the lab.

2. At a temperature of 180° C. (the temperature you will use), calculate the mean kinetic energy of a mercury atom in electron volts and discuss whether excitations can occur even if the electron has considerably less electrostatic energy than V_{ex}. How observable should this temperature effect be? Note that there is little net kinetic energy transfer from electrons to atoms through *elastic* collisions; assume that the mean K.E. of mercury atoms (their temperature) does not vary with V.

3. Why must the gas tube be heated (In what form is mercury at room temperature and pressure)?

4. Mercury has a number of excitation potentials, which we did not include in drawing Figure 3. What would Figure 3 look like if you included a few of the possible transitions between energy levels shown in Figure 1? Assume all transitions have roughly the same probability of occurring. You needn't accurately show the exact energies, but rather just show the general appearance of the plot. (hint: Consider that each transition should cause a `dip' in Figure 3, as should any combination of two or more transitions in one or more atoms, generated by one electron with sufficient energy).

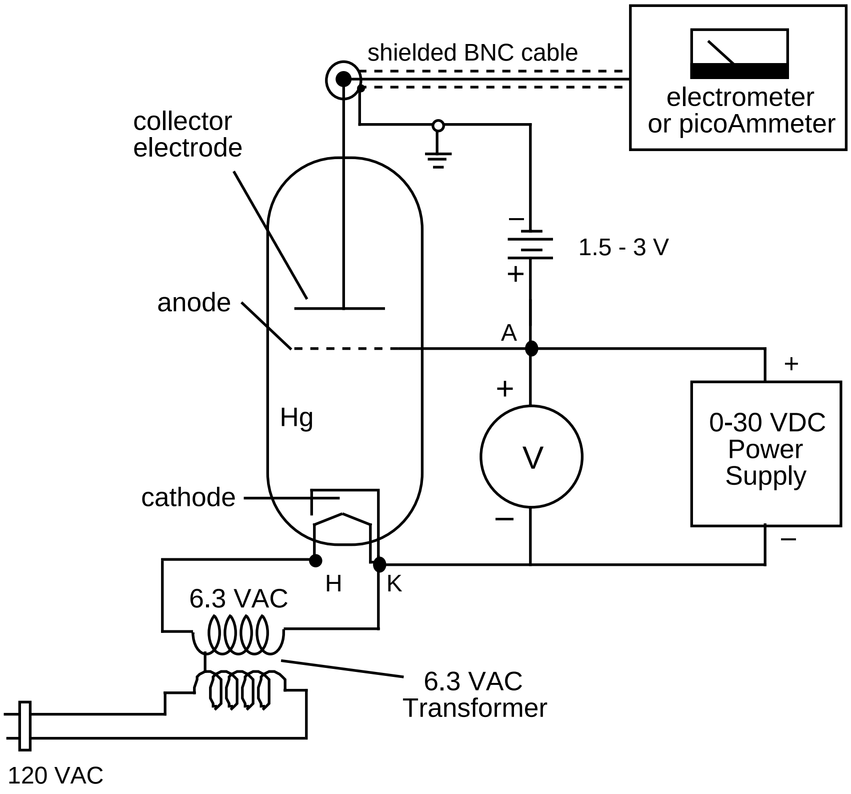

Figure 4. Schematic diagram

THE APPARATUS

A schematic of the circuit which you will use is shown in Figure 4. The power supply applies a negative potential to the cathode to accelerate electrons toward the anode. The 10 kilohm resistor prevents ionization as discussed above. The electrometer is a current meter with an amplifier which allows measurement of currents as small as a few picoamperes (1 picoampere = 10^{-12} amperes). The dotted lines running to the Electrometer represent the outer cylindrical conductor of the coaxial cable, just under the plastic insulation, and is connected to ground. The perforated anode is held at some small retarding voltage ΔV above ground by two dry cell batteries. The 5 kilohm potentiometer allows you to choose ΔV between 0 and 3 volts. The tube itself is mounted inside a thermostat-regulated oven to maintain the mercury gas in optimum condition for your measurements.

PROCEDURE: PRELIMINARY ADJUSTMENTS

1. Plug in the power cord for the oven heater, and insert the thermometer so that the bulb is at the same height as the center of the tube. A few turns of masking tape around the thermometer will prevent it from falling into the oven. The best oven temperature for this experiment is about 180° C., and the oven can be maintained near this temperature by the thermostatic control on the side of it. The thermostat knob is turned {clockwise} to increase the temperature setting; if turned too far, it will click to indicate that the thermostat is back at its lowest setting. Never turn the knob back (counterclockwise) through this click position. It is all right to make *small* counterclockwise adjustments as long as you do not turn through the click position.

2. The rest of the apparatus can be connected while the oven heats. The oven front panel contains a circuit schematic to assist you. Place the oven so that you can see through the window in the back {and} make connections to the front panel. Assemble the equipment as shown in Figure 4. Before plugging in the power cables, turn the power supply control to its lowest setting.

3. Connect a coaxial cable to the Input terminal (the other end should be connected to the collector electrode, with the black lead grounded). The Output terminal is used for operating a chart recorder, and will not be used in this experiment.

EXPERIMENTS

1. Increase the accelerating potential slowly, while watching the value of the collector current indicated by the electrometer. It will be necessary to use a different range on the electrometer for the smaller accelerating potentials, but be sure not to `pin' the electrometer needle to its maximum deflection. Notice the behavior of the electrometer needle as you increase V. from 0 to about 30 volts. It should show dips in current at several values of V..If the dips in the current are not deep, you may be able to improve matters by making small adjustments in the oven temperature.

Disconnect the electrometer input and check that the electrometer is zeroed and calibrated. Now, starting again at 0 volts, take data so you will be able to plot collector current as a function of accelerating potential.

To estimate measurement errors, allow the accelerating voltage to remain constant while the oven goes through a few cycles (watch the thermometer). Record the fluctuations of current and temperature (voltage should not change).

2. Measure *I* and *V*. (just their several minima and maxima) for an additional two or more temperatures, say 150°, 160°, 170°, 190° C to see if your results are temperature dependent.

ANALYSIS & QUESTIONS

1. Make a plot of Electrometer current *I* vs power supply voltage (accelerating potential) *V*. Do the maxima and minima all have the same spacing? What is the first excitation potential V_{ex} of mercury in electron volts? in Joules? Why is the first minimum of *I* at a voltage that differs from your value of V_{ex}?

2. How would your *I* vs *V*. plot appear if the atom energies were {not} quantized?

3. Assuming everything else were unchanged, what would be the effect on the *I* vs *V*. graph of the following: {a.} increasing the retarding potential ΔV. {b.} decreasing the retarding potential ΔV. {c.} reducing the voltage applied to the cathode. {d.} increasing the density of mercury in the tube (careful!). Give a brief physical explanation for each effect.

4. Do higher excitations (second, third, etc. excited states) appear in your *I* vs *V*. plot? Comment briefly in light of your answer to prelab question 4.

5. Do the acceleration voltages for minimum current depend on temperature? How about their spacing, V_{ex}? Do the values of maximum and minimum current themselves depend on temperature? What physical reasons can you give for the temperature dependences you observe?

6. Explain what occurs in the tube at potentials corresponding to the second dip in current in your plot.

7. (optional) Explain the bright bluish spot. What is occurring to produce all those emission lines? (Hint: Consider ionization. Why doesn't the 10 kΩ resistor stop it completely? Hint 2: The rating of 6.3V on the transformer is a root mean squared value, and in addition may be exceeded slightly.)