

6 The Franck-Hertz experiment

Abstract: In this lab you will measure the first excitation energy of Mercury by carrying out a modern version of the landmark experiment reported by James Franck and Gustav Hertz in 1914.

6.1 Pre-lab preparation

In the atomic spectra lab, you saw that atoms emit photons of specific, quantized energies. In this lab, you will see that they also absorb energy in quantized amounts from electrons.

Franck and Hertz didn't set out to validate quantum theory. They conceived the experiment in 1911, well before Niels Bohr proposed his model of the atom, with the aim of better understanding electron conductivity through gases. But by the time they built their experiment, collected their data and reported their results it was 1914. The Bohr model was about one year old. Their data offered unequivocal evidence that an atom can accept energy only in discrete amounts. It was crucial to the acceptance of quantum theory because, at that time, photons were still somewhat mysterious but electrons were unquestionably real particles whose kinetic energy could be readily determined.

The experiment generates a current of electrons from a cathode and accelerates them with a voltage on an anode, V_a , so the maximum kinetic energy that can be obtained by the electrons is eV_a . A low pressure gas of mercury atoms in the region between the cathode and anode causes the moving electrons to scatter off the mercury atoms. If the atoms could absorb any energy from the electrons, we'd expect that the electrons would lose energy even when they are moving slowly. But, if the atoms can only absorb discrete energies from the electrons, then we'd expect to see a sudden onset of energy transfer only once the electrons' kinetic energy becomes equal to the lowest (or first) excitation energy of the mercury atoms. By slowly increasing V_a and measuring the kinetic energy of the electrons that reach the anode, we can test this expectation. A sudden drop should occur when eV_a reaches the first excitation energy eV_1 .

If the voltage is increased above V_1 , an electron that excites a mercury atom in one collision can regain energy after the collision. When V_a reaches $2V_1$, it becomes possible for an electron to undergo two interactions, and be left with little energy when it reaches the anode. This continues as the voltage is increased further; we should see drops in the electrons' final kinetic energy each time V_a crosses an integer multiple of mercury's first excitation energy.

There are two complications in the actual experiment. First, it is not easy, or necessary, to directly measure the final kinetic energy of the electrons. It is simpler, and sufficient, to just measure how many electrons are above some kinetic energy threshold. We can do that by using a grid for the anode, so the electrons can pass through it, and then placing a third electrode beyond it. Applying a retarding voltage, $V_r > V_a$, to that third electrode will allow only electrons with kinetic energy above $e(V_r - V_a)$ to reach it. (Ask yourself: Where will the other electrons go?) Measuring the current collected by the third electrode will measure how many electrons have sufficient kinetic energy to reach it. We can detect when there is a drop in electron kinetic energy due to excitation of the mercury atoms by observing a drop in the current through the "collection electrode".

The second complication is that there are small offsets to the kinetic energy of the electrons due to the contact potential of the electrodes. For example, the thermionic emission of electrons from the cathode requires a small amount of energy, similar to the work function of the metal that we encountered in measurements of the photoelectric effect. The voltage when the first drop occurs is not a good measure of V_1 due to bias from these offsets. However, measuring the *difference in voltage between subsequent*

current drops removes the bias and can be used to determine V_1 .

6.1.1 Apparatus

A diagram of the apparatus you'll use is shown in Figure 21. A photo of the apparatus you'll use is shown in Figure 22. In the diagram, the volume containing gas is depicted as an ellipse. The cathode, with its heater, is at the bottom of the volume, both in the diagram and inside the apparatus. The anode grid is represented by a thick, dashed line, and above it the collection electrode is represented by a thick, solid line. The gas volume is housed within an oven that is heated by the power supply at the upper left, and its power is controlled by the large variac. To produce thermionic emission, the cathode is heated by a filament controlled by the smaller variac, shown at the bottom left. The anode voltage, V_a , is set by the power supply, and adjusted with a variable resistor. The retarding voltage on the collection electrode, V_r , is set by a 1.5 V battery with a variable resistor. Each of the voltages, V_a and V_r , are measured by voltmeters. The current reaching the collection electrode is measured by the electrometer, which is the same device you used in the photoelectric effect lab.

6.1.2 Safety and care of equipment

The potential hazards in this lab involve the high temperature of the oven and the moderately high voltage of the power supply. Both hazards are mitigated by being contained within enclosures.

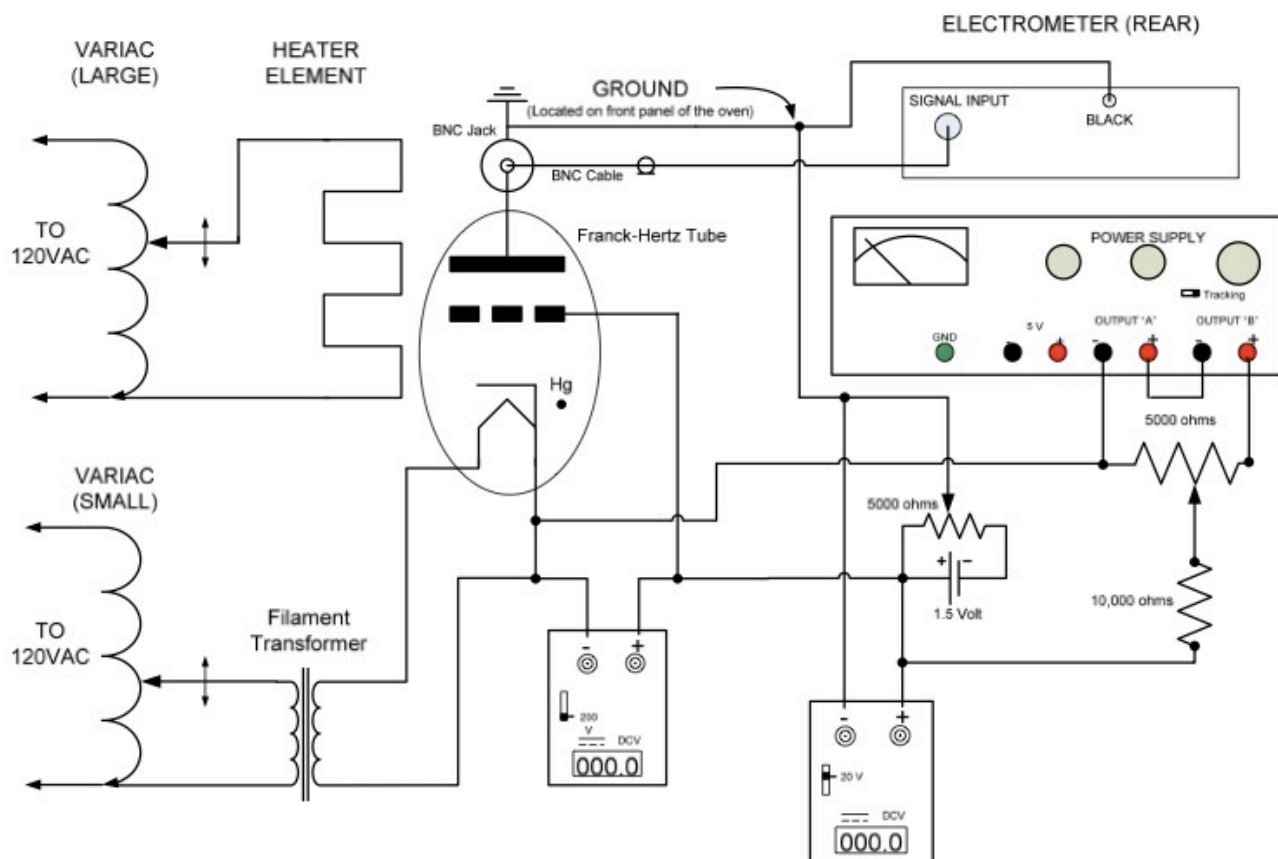


Figure 21: Diagram of the apparatus.

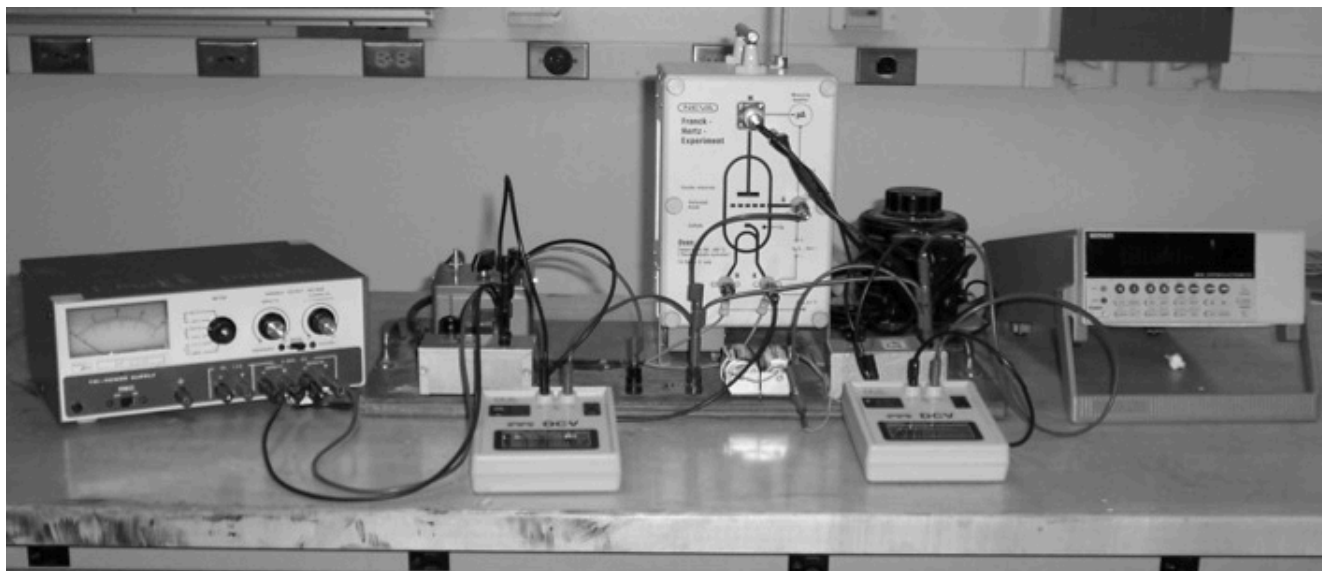


Figure 22: Photo of the apparatus.

6.2 Getting started and gaining familiarity

The first thing to do is insert the thermometer into the oven so that its bulb is even with the mid section of the tube. Then turn the oven on. (Both of these things may have been done for you, as it takes the oven, and the room itself, a while to stabilize in temperature.) The target temperature is in the $170^{\circ} - 190^{\circ}\text{C}$ range. It can be adjusted with the large variac knob. You should set it initially to about “78” on the variac’s scale, but monitor the temperature frequently and adjust accordingly. Note that the thermal response time is large. It may take 10 - 15 minutes to warm up, and adjusting the variac knob will not cause an immediate change. It is best to make small changes and monitor frequently.

Check the setup and confirm that it is wired as shown in Figure 21(a). Ask for assistance if anything does not make sense.

Turn on the electrometer and correct any zero offsets. The procedure for this is the same as in the photoelectric effect lab, and is listed again, for your convenience, in Figure 23.

Zero Correction procedure to remove offsets

- Enable Zero Check mode. Press ZCHK; you should see a “ZC” message appear at the right side of the display.
- Select the current measuring mode by pressing I (if not already in that mode).
- Select the appropriate measurement range.
- Perform a zero correction by pressing ZCOR; you should see a “ZZ” message appear in the display.
- Press ZCHK to disable the Zero Check mode; you should now see a “CZ” message appear in the display to indicate that the subsequent readings are corrected for any zero point offsets.

Figure 23: Zero correction procedure.

Once the oven temperature has stabilized at about 180°C , set the retarding potential to 1.3 V and then turn on the power supply. Be sure that the power supply is set to “Tracking mode” and the output voltage is set to 40 V (far right knob, or “master control”, depending on the power supply model). Then adjust

the $5\text{k}\Omega$ potentiometer that controls V_a up until you measure about 40 V on V_a 's voltmeter.

Set the knob on the small variac to zero and then turn on the small variac. This variac controls the cathode's filament heater, which causes electrons to be thermionically emitted from the cathode. Slowly increase the small variac's knob until you get a current reading on the electrometer of between 0.75 and 1.0 nA, but don't go beyond that current. **Caution:** if you exceed 1 nA before the variac has been turned more than about halfway, shut it off immediately and notify the TA.

Now that everything is on and functioning, you can begin making measurements.

6.3 Measuring the excitation energy

If you followed the directions described above, V_a is set to the highest value (40 V) you'll want to use. Take a first round of data by reducing V_a by 0.5 V at a time and noting the electrometer current, I . This is coarse measurement, so don't bother waiting very long for the current to settle to a stable value. Give it a few seconds and just jot its value down. After you've collected a few dozen data points, in this crude way, plot your data. Write down salient details of what you notice in your logbook. Then go back to taking crude data until you get to $V_a = 0$ V. Again, plot your data and note any thoughts you have about it in your logbook. In particular, think about what clues this crude data offers for how you should go about taking precision data.

Make your first pass at taking precision data by increasing V_a while monitoring I . It should increase at first, and then decrease after it crosses the point where electrons can excite mercury atoms. Collect data that will let you identify the V_a at which I peaks. Make sure to describe your procedure for doing so in your logbook. Then continue to increase V_a and you should see that the current goes through a minimum. Collect data that will let you identify the V_a at which I is its lowest. Again, make sure to describe your procedure for doing so in your logbook.

Continue to increase V_a and similarly record the voltage and current for each of the subsequent peaks and minima until you reach the maximum possible value of $V_a = 40$ V. You should see about six cycles of current peaks and minima.

In addition to recording near the peaks and minima, you should record I and V_a at a few points between them. This will allow you to make a plot of the full $I(V)$ curve that illustrates the overall behavior.

Determine the first excitation energy of mercury. Keep in mind that the absolute voltage is biased by potential offsets so, as explained in the introduction, instead of using the voltage values directly, you should use the differences between consecutive peaks or consecutive minima for your measurement.

6.4 Going Beyond

While you can obtain a measurement from a single scan, or even from just a couple peak positions, it is always a good idea to measure things repeatedly. Measuring the variation between multiple measurements helps to validate the results. You would be wise to take more than one scan.