PHYSICS 258 Lab Manual[1]

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[1]Updated: February 14, 2021

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Lab 4

The Franck-Hertz Experiment

Learning Objectives

- To investigate the influence of filament voltage and retarding voltage on current.
- To verify the theory of energy quantization.

Introduction

In 1914, James Franck and Gustav Ludwig Hertz presented the first electrical measurement displaying the quantum nature of atoms [1]. Franck and Hertz designed a tube that allowed electrons to fly through a thin cloud of mercury vapour. They noticed that the electrons could only lose specific amounts of energy during a collision with a mercury atom, namely, 4.9 eV. Later, they showed that this energy drop corresponded to an ultraviolet line in the emission spectrum of mercury thus confirming the Bohr model of the atom from the previous year! It gave evidence for the existence of discrete atomic shells and orbitals. Franck and Hertz later on won the Nobel Prize in Physics in 1925 for their discovery of "the laws governing the impact of an electron upon an atom" [2].

In this laboratory, we will mimic the experiment done by Franck and Hertz in 1914 using Argon as our gas instead of mercury.

Theory and Experiment

The essence of the experiment is energy conservation. A schematic of a Franck-Hertz tube is shown in Figure 7. Electrons are released from the heated filament and they all gain the same amount of kinetic energy as they are accelerated by the potential difference between cathode and grid. For example, a grid potential of 1 V relative to the cathode or filament will accelerate the electron to 1 eV of kinetic energy. Once electrons pass through the grid they are decelerated by a reverse bias and measured as they land on the anode. Only electrons with a kinetic energy that exceeds the reverse bias will arrive at the anode plate and register as a current. Atoms (vapour or gas) fill the volume between grid and anode. Electrons lose energy as they collide with these atoms, and only those with sufficient kinetic energy to overcome the reverse bias potential are read as a current.

Electrons with less kinetic energy than a specific amount (4.9 eV in the case of mercury) bounce off the Hg atoms without losing any significant amount of energy. They undergo an elastic collision where the direction of their motion may be altered while their speed is not (or at least, not significantly). The electrons can still reach the anode and register as a current.

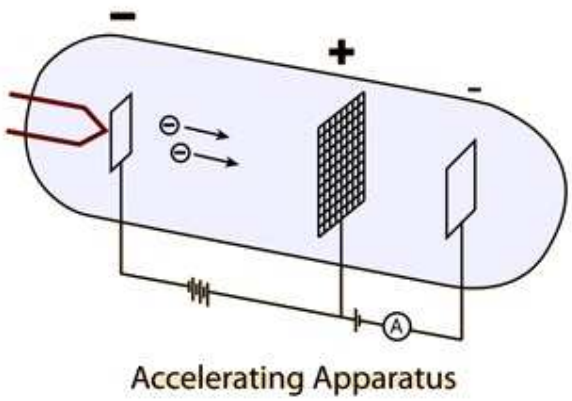

Figure 7: Schematic of the Franck-Hertz tube . See text for details. Adopted from [3].

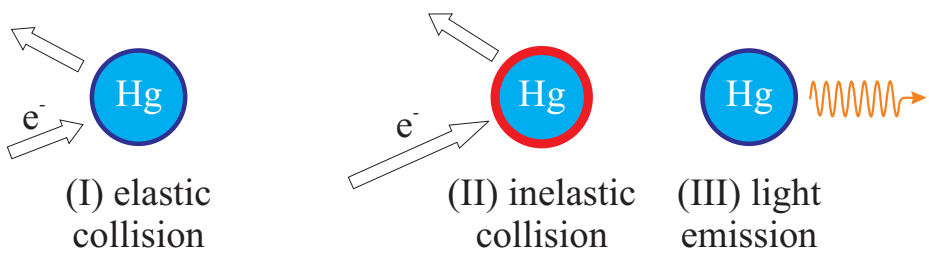

Figure 8: (I) Elastic versus (II) Inelastic collision of an electron on a Mercury atom. (III) Light emission follows inelastic collisions.

Once the accelerating potential exceeds an energy threshold ($K_E > 4.9\,\text{eV}$ in the case of mercury), electrons will collide inelastically with the atoms and lose an element-specific amount of kinetic energy (exactly 4.9 eV for Hg). The atoms motion is essentially unaffected by the collision as its mass is approximately 4×10^5 that of the electron [4]. So where does the energy go? The lost kinetic energy K_E excites a bound shell electron in the atom to a higher energy level (see Figure 8). The excited shell electron then returns to its initial state under the emission of a photon. The electron will be re-accelerated by the electric field. Depending on where along the electric field the inelastic collision occurred, i.e. depending on the strength of the applied electric field, the electron might gain sufficient energy to overcome the reverse bias and register as a current. If the accelerating field is strong enough, electrons will even undergo further inelastic collisions.

Franck and Hertz used a tube filled with Hg vapour where they observed the current to initially increase steadily with the grid-potential, similar to what would occur with a vacuum tube. Once they went above 4.9 V, they began to notice a decrease in current, bringing the current almost to zero before steadily increasing again with further increasing grid potential. The dips occurred periodically at intervals of 4.9 V. This pattern continued to a grid voltage of about 70 V, which demonstrated that electrons bound to an atom cannot be in a continuum

of energy levels but rather must occupy quantized energy states.

The 4.9 eV is due to a specific difference in energy levels in the mercury atom, namely the ground and first excited states. This was first noticed when Franck and Hertz measured the emission of light from their tube. They noticed ultraviolet radiation at a wavelength of 254 nm being emitted from the tube, as illustrated in Fig. 7, corresponding to an electron transitioning from an excited state to the ground state, 4.9 eV below. The conversion between the emitted photons' wavelength and its energy is given by $E = h\frac{c}{\lambda}$, or $E = h\nu$, as explored in the photoelectric effect experiment.

After a presentation of these results by Franck a few years later, Albert Einstein is said to have remarked,"It's so lovely it makes you cry" [5].

Note: The following is adapted from the Pasco Franck-Hertz Instruction Manual [6].

Procedure Part 1: Setup

1. **Before** connecting up the apparatus, make sure all power supplies and amplifier are OFF (check that switches are in OFF position) and the dial knobs are set to zero (turned all the way counter-clock wise). Check the correct power supply settings:
   - For *DC Supply I* make sure the orange button is pushed IN and set at the $-4.5\,\mathrm{V}\ldots+30\,\mathrm{V}$ setting.
   - For *DC supply II* make sure the button is OUT and set at the $0-100\,\mathrm{V}$ setting.
2. You may now connect up all of the apparatus according to the circuit diagram in Figure 9 with everything turned OFF, e.g. power button not pushed in. *Make sure to check your connections with a TA or technician before moving forward.*
3. Connect the BNC cable from the Franck-Hertz tube to the *DC Current amplifier*.
4. Connect the 8-pin DIN sensor cable to the PASCO interface and the PASCO interface to the computer using the USB cable.
5. Turn ON the power for the Universal Interface and the power supplies.
6. Turn on the current amplifier and adjust the current range knob to the 10^{-10} setting and calibrate the *DC Current amplifier*:
   - Open up the Franck-Hertz Capstone file, go to the $\boxed{\text{Calibration}}$ tab and press monitor.
   - Make sure to not move the BNC cable and to try and minimize vibrations on the table as these will affect the reading.
   - Press the orange button IN.

- Turn the current-adjust dial on the amplifier until the current on the computer screen reads zero or fluctuates on either side of, and as close to, zero as possible.
- Press the orange button again such that it is in the OUT position, you have now calibrated your apparatus and the *DC Current amplifier* is ready to start taking data.

7. On *Power Supply I*, rotate the -4.5 ...+30 V adjust knob until the voltmeter reads 1.5 V. This sets Set V_{G1K} at 1.5 V (the voltage between the first grid and the cathode).
8. On *Power Supply II*, rotate the $0 - 12$ V adjust knob until the voltmeter reads 9.5 V to set V_{G2A} at 9.5 V (Retarding voltage).
9. On *Power Supply II*, rotate the $0 - 100$ V adjust knob until the voltmeter reads 0 V. This sets V_{G2K} at 0 V (Accelerating voltage).
10. Look up the filament voltage V_H on the argon tube enclosure (this should be a value around 3 V).
11. On *Power Supply I*, rotate the $0 \rightarrow 6.3$ V adjust knob until the voltmeter reads the filament voltage V_H.
12. **Allow the filament and argon tube to warm up for 15 minutes!**
13. Before you continue, double-check the applied voltages:
    - $V_{G1K} = 1.5$ V
    - $V_{G2A} = 9.5$ V
    - V_{H}, check value posted on argon tube enclosure.

Procedure Part 2: Data Taking

Open up the Taking Data tab in the capstone file, and make sure you waited 15 minutes for the tube to warm up before continuing.

Now, press Preview and begin taking data by pressing Keep Sample when you are satisfied with a data point. Increase the accelerating voltage V_{G2K} by 2 V and press Keep Sample again. Repeat this up to 80 V. Do not go over the 80 V limit as this can damage the Franck-Hertz tube. Notice the peaks and troughs of the graph. You will need to go back to these relative maxima and minima and collect more data points in order to have well-defined peaks and troughs. To do this, turn the dial back to $V_{G2K} = 0$ V and repeat the measurement up to 80 V. As you approach the peaks and troughs, record data at 0.5 V intervals instead of 2 V intervals on either side of the peak or trough. Do not go overboard; two points on either side is enough. The current of your second measurement may differ from the first run through. This is OK as long as the positions of peaks and troughs do not change.

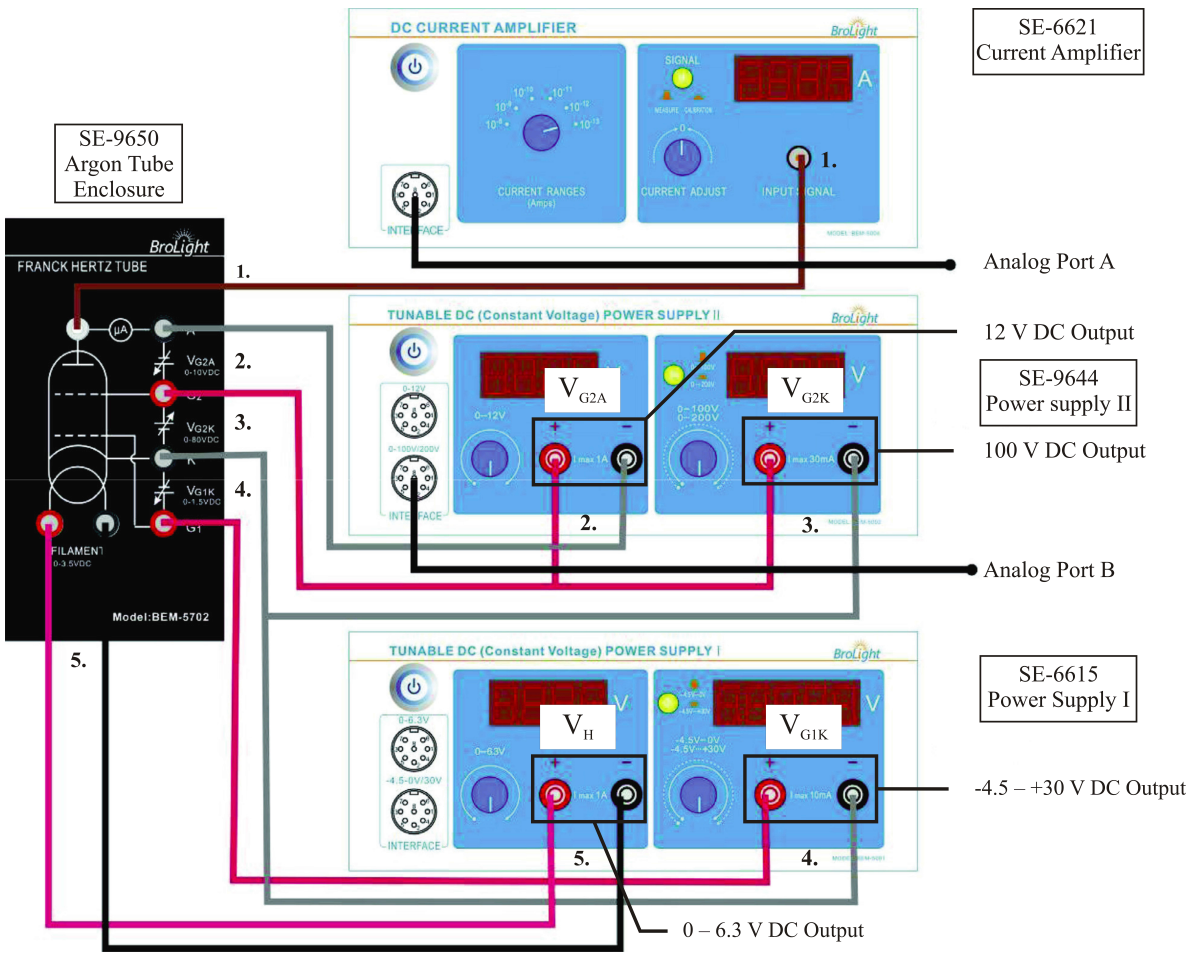

Figure 9: Experimental setup showing the wiring connections. Adopted from [6].

Once you have gone back over the last peak (lowest accelerating voltage) press Stop and then press the Data Summary button on the left of the screen and rename your trial to whatever you wish. Now go to your graph and use the coordinate tool (square target) to get the x-axis values of your peaks and troughs. You may scroll your mouse to zoom and out of the graph as necessary. Record these values in the table to your left. The difference between columns will fill up automatically.

To display multiple data sets on your graph or remove some from the display, toggle the multi-coloured triangle above the graph and use drop-down arrow on its left to select which data sets to display. Similarly, this can be done by pressing run tabs above your column titles in the table.

Procedure Part 3: Data Taking with Different Parameters

1. Repeat the experiment with all the original parameters except now use $V_{G2A} = 10.5\,\mathrm{V}$.
2. Repeat the experiment one more time with the original parameters except increase the filament voltage V_H by $0.5\,\mathrm{V}$.

Analysis

- What is the average difference between the peaks and troughs of the graph for each trial, quoted with uncertainty?
- Calculate the excitation energy of argon and compare it to literature values.
- Calculate Planck's constant h using literature values (don't forget to reference the values). How does your measurement compare to literature values?
- Do the different parameters affect the difference in these peaks and troughs, i.e are they more or less spread out?
- If they are not consistent with each other, how significant are these findings?

References

[1] Franck, J., and Hertz, G. (1914). *Über Zusammenstöße zwischen Elektronen und Molekülen des Quecksilberdampfes und die Ionisierungsspannung desselben* (On the collisions between electrons and molecules of mercury vapor and the ionization potential of the same). Verhandlungen der Deutschen Physikalischen Gesellschaft 16: 457?467

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[6] Pasco Franck-Hertz Experiment. Model SE-9639 Instruction Manual 2015