# Franck-Hertz Experiment for Neon and Argon

Alisha Vira and Ning Zhu

*Affiliation not available*

Nathanael A. Fortune

*Smith College*

## Abstract

## AIMS

The goal of the Franck-Hertz experiment is to demonstrate that electrons occupy only discrete, quantized energy states for neon and argon atoms.

## INTRODUCTION

Bohr's theory is one of the most important models in modern physics, and it was first confirmed experimentally by James Franck and Gustav Hertz in 1914. Bohr model suggests that electrons only occupy discrete energy levels, which is a significant modification of classical physics. The purpose of this lab is to reproduce the Franck Hertz experiment with argon and neon atoms, and to see whether the lab results are consistent with the theoretical values.

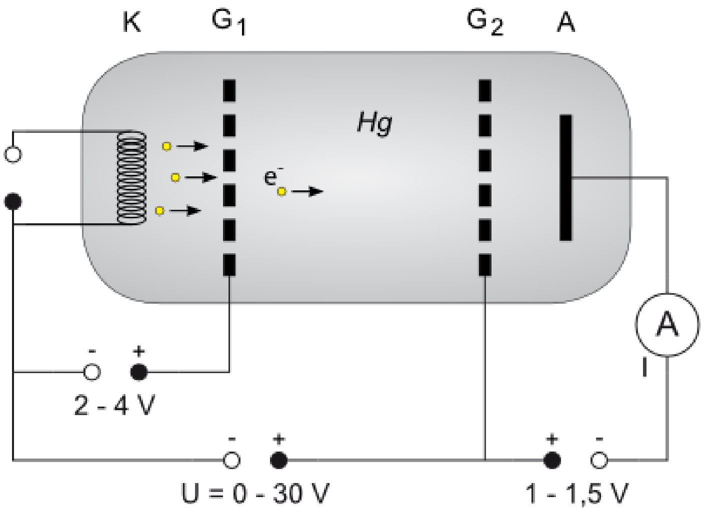

Figure 1. Schematic diagram of the Franck-Hertz experiment

The basic apparatus of Franck Hertz experiment is shown in Fig. 1. Argon tube and neon tube are used in this experiment. The tubes are highly evacuated and are filled with atoms. Within each tube, there is a filament, a control grid, an accelerating grid, a cathode and an anode. An accelerating voltage is applied between cathode and accelerating plate to provide electrons with kinetic energy. A retarding voltage is applied between anode and accelerating plate to attract more electrons to the anode. Control grid is necessary for argon and neon, but will be unnecessary for some atoms such as mercury. The function of the control grid is to attract more electrons from the filament. Electrons are emitted from the filament when the heating voltage is applied.

As we increase the accelerating voltage, electrons are gaining more and more kinematic energy and they are colliding with atoms elastically until the kinematic energy reaches the first excitation level of the atom. When the first excitation level is reached, inelastic collisions occur and the electron will transfer all the kinematic energy it has to the atom (refer to Fig. 2). This corresponds to a dip in current detected by the anode due to the sudden decrease of electrons that reach the anode. As the accelerating voltage keeps increasing, there will be more dips, corresponding to multiple integers of inelastic collisions happened in the tube. These dips in current explained the quantum nature of atoms.

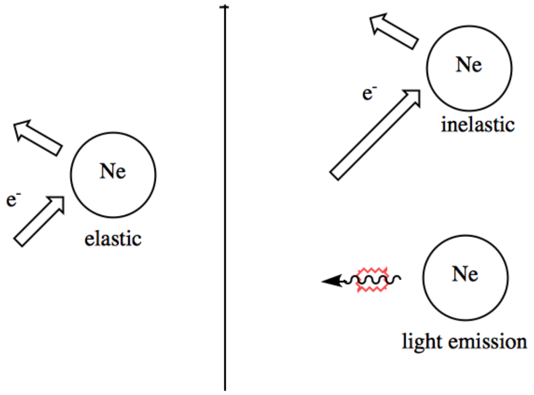

Figure 2. Illustration of the elastic and inelastic collisions with neon atoms. The left side of the figure displays the atomic behavior before the electron has enough energy to excite the atom. Whereas, the right displays the behavior once the electron has enough energy to excite the atom.

The distance the electron travels before colliding with an atom and exciting it is called the mean free path. The mean free path can be calculated using the equation below:

$$\lambda = \frac{L}{2E_a}\frac{d\Delta E(n)}{dn}$$

where $\lambda$ is the mean free path, $L$ is the distance between accelerating grid and control grid, $\Delta E(n)$ is the spacing between two minima in Franck Hertz experiment, $n$ is the minimum order and $E_a$ is the lowest excitation energy.

As the applied accelerating voltage increases, electrons continue to gain energy along their mean free path and could possibility also excite the higher energy levels of the atoms. Since electrons gain additional accelerating energy as the number of inelastic collision increase, this means that if an electron inelastically collides twice with atoms their total energy gained is

$$E_2 = 2E_a + 2\delta_2$$

. For n inelastic collisions, the total energy gained by an electron can be expressed as below:

$$E_n = n(E_a + \delta_n) \text{ where } \delta_n = n\frac{n}{L}E_a$$

.

The two equations above can be used to derive an expression for the spacing between two minimas (refer to Appendix A). The expression $\Delta E(n) = [1 + \frac{n}{L}(2n-1)]E_a$ shows that the spacing between two anode voltage minima is increasing. The lowest excitation level can be derived by setting n=0.5.

$$E_a = \Delta E(0.5) \tag{1}$$

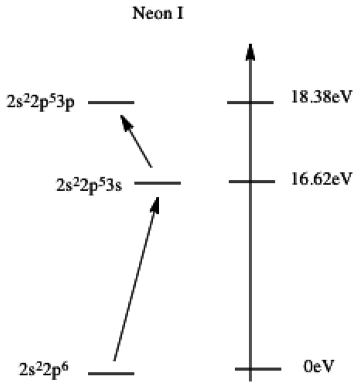

Figure 3. Energy levels for Neon I, according to NIST.

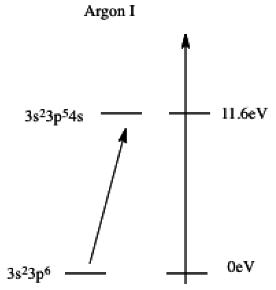

Figure 4. Energy levels for Argon I, according to NIST.

Ne atoms have only been excited to the first and second energy level; whereas, Ar atoms mainly stay in the first energy level. According to the NIST Atomic Spectra Database, the first excitation energy of Ne I is 16.62eV, and the second excitation energy level is 18.38eV (Fig. 3). For Ar I, the four sub levels within the first energy level are 11.55eV, 11.62eV, 11.72eV and 11.83eV respectively (Fig. 4). In this lab, we will be studying the distance between the minimas to see if it corresponds to the energy levels of neon and argon.

## METHOD

The neon and argon experiments were based off of the basic apparatus shown in Fig. 1. All the wiring was essentially the same. However, the most important concept is the different setting for the voltages supplied to the different parts of the apparatus.

### Neon Experiment

The two most important pieces of equipment consists of the DC Power Supply (Keithley 2230-30-1) and the function generator. These two pieces of equipment was supplying a voltage and a waveform for the neon tube. The DC Power supply was supplying voltages to the heater, control grid, and reverse bias. Whereas, the function generator was supplying a ramp waveform to the neon tube.

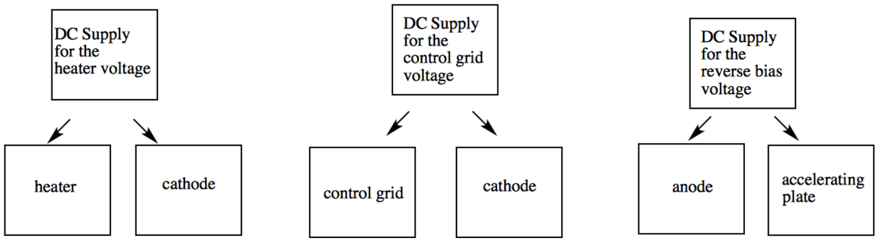

Figure 5. Schematic diagram of the power supply connections for the neon tube

Each of the power supply outputs serves a key purpose in the apparatus. The heater voltage heats the cathode so that it will produce enough electrons. For instance, if the heater voltage is too low then the experiment will not work out because the cathode will not heat enough electrons for anything to be measured. Whereas, if the heater voltage is too high then the filament could blow or the neon atoms could also be ionize.

The second channel controlled the control grid voltage. This voltage was not as tricky to set as the heater voltage because primary purpose was to attract the electrons from the filament to the the grid so that the experiment can be observed.

Lastly, the reverse bias voltage from the power supply was another key voltage to set. To illustrate its function, if the reverse bias voltage was too low then the electrons would not be attracted towards the plate measuring the number of electrons which produced the graph that allows us to study the discrete energy levels of neon.

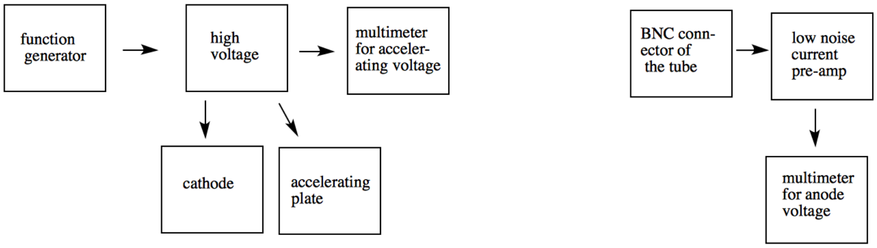

Figure 6. Schematic diagram of the function generator and multimeter connections.

In order to better observe the discrete quantized energy levels, a high voltage device is needed to amplify the function generator output by 20V. And this high voltage output will be applied between the cathode and accelerating plate to give the electrons enough energy. And another set of output leads would be put into a multimeter to measure the accelerating voltage.

When measuring the anode output, a low noise current preamp (Stanford Research Systems Model SR570) should be connected to clean up the signal. This stabilizes the anode voltage by applying a 12dB low pass filter that allows us to filter out the unwanted frequencies.

To recap the two voltages that are being measured, there is the anode voltage which measures the electrons hitting the last plate in the tube and there is the accelerating voltage that measures the voltage applied to the system. In order to obtain more information on the quantum nature of atoms, the anode current plotted against the accelerating voltage would provide a general idea of the excited energy levels.

| PRE-AMP | FUNCTION GENERATOR | DC POWER SUPPLY |
|---|---|---|
| Filter Frequency: 30Hz | RAMP cycle | Heater Current: 0.142A |
| Sensitivity: 5 nA/V | Period: 500s | Control Grid Voltage: 5.296V |
|  | HiLev: 4V | Reverse Bias Voltage: 6V |

| PRE-AMP | FUNCTION GENERATOR | DC POWER SUPPLY |
|---|---|---|
| Filter Frequency: 3Hz | RAMP cycle | Heater Current: 0.779A |
| Sensitivity: 20pA/V | Period: 4ks | Control Grid Voltage: 1.49V |
|  | HiLev: 6V | Reverse Bias Voltage: 11.5V |

Our settings can be summarized in the table below:

### Argon Experiment

This experiment had an identical wiring to the neon experiment. The main difference was the voltage settings for the DC Power Supply.

After adjusting the voltages until we were able to optimize the anode current verses the accelerating voltage graph, we ended up with these settings:

A common issue was encountered that for the argon experiment was grounding. Since it is very hard to see the connections inside the argon or neon tube, the best way to debug the grounding issues was by guessing and checking. For the argon experiment, we had a grounding issue between the cathode and heater. This was simply solved by connecting a wire between those two points. However, every tube is different, which means that the apparatus should always be tested more than once before sending high voltage and current through the circuit.

## RESULTS

We plotted anode voltage as a function of accelerating voltage for both neon and argon. Generally, the curves come out as we expected. However, the neon curve goes up a lot but the argon curve does not. This is a result of the affect of the background. Therefore, we removed the background of neon data. In order to see where the dips occur, we took the derivative of each point and plotted the derivative as a function of accelerating voltage. We identified the dips by looking at where does the derivative curve across X-axis with a positive slope. We then plotted the spacing between two dips as a function of the dip order.

### Neon Experiment

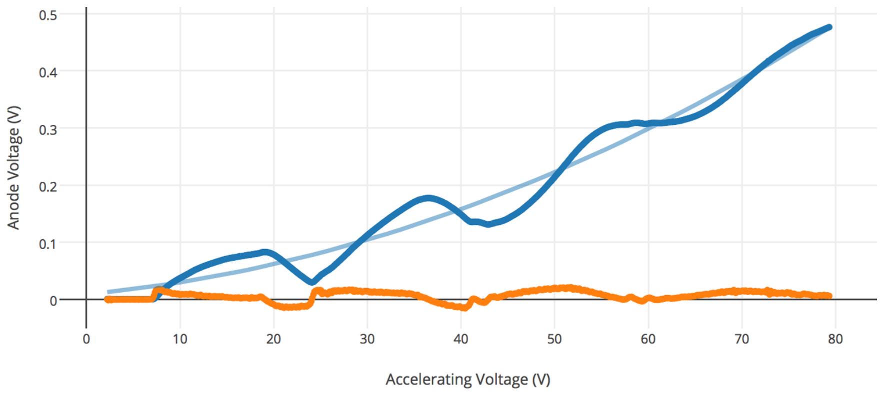

Figure 7. Displays the accelerating voltage verses the anode voltage. The blue curve represents the data taken directly from the multimeter. The orange curve represents the derivative of the blue curve at each point. And the light blue curve represents the background for this experiment.

### Argon Experiment

## ANALYSIS

### Neon Experiment

Using 9 and Eq. 1, we plugged in x to be 0.5 to find the excitation level for each of the linear fits shown in the plot. This generated a excitation energy of $19.4993 \pm 0.6$ eV. This has to be the first excitation level because we derived Eq. 1 by setting $E_a$ equal to the lowest energy level. However, this is not consistent with the first excitation energy level shown on the NIST website. (Fig. 3.)

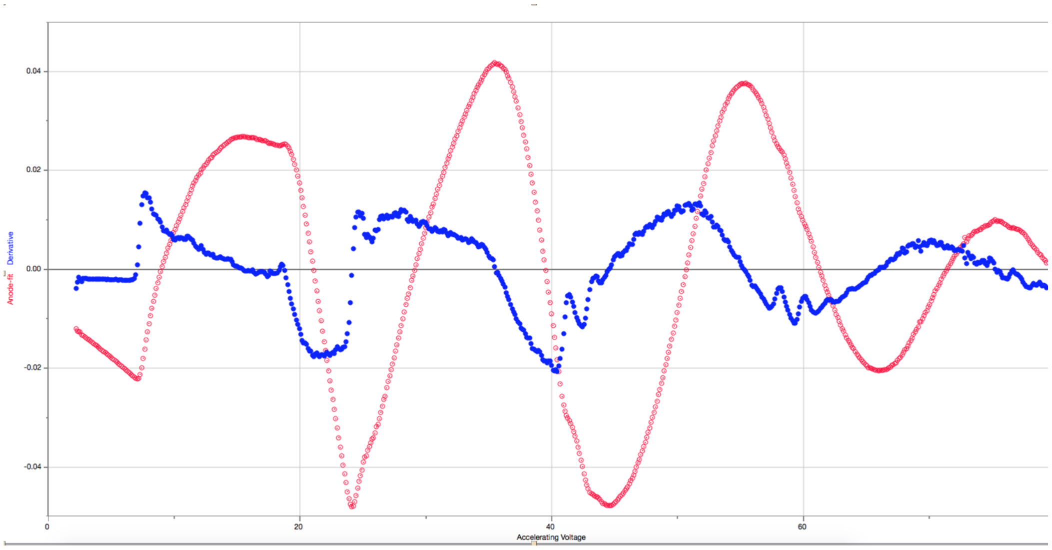

Figure 8. Accelerating voltage versus the background minus the anode voltage. The red curve is the data after the background was subtracted from Fig.7. Whereas, the blue curve is the derivative at of the red curve at each point.

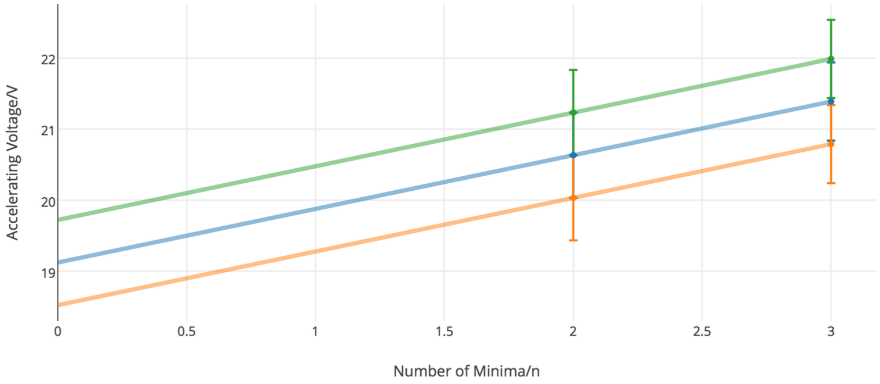

Figure 9. Spacing between minima in voltage versus the number of minimum n for a neon tube. The maximum and minimum of spacing when taking error bars into account are also shown. The three corresponding linear fits are shown in the graph as well. The blue linear fit is the fit through the middle of the error bars. Whereas, the orange fit shows the lowest values within the error bars. And the green fit displays the highest values within the error bars.

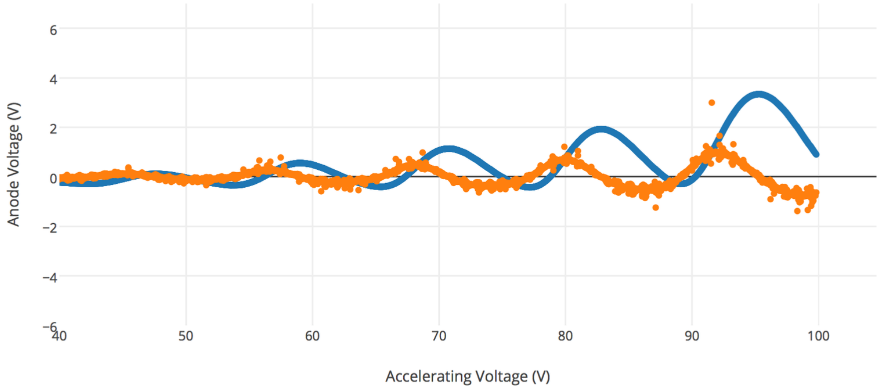

Figure 10.  Displays the accelerating voltage versus the anode voltage. The blue curve represented the voltage measured from the output of multimeter. Whereas, the orange curve represents the derivative at each point.

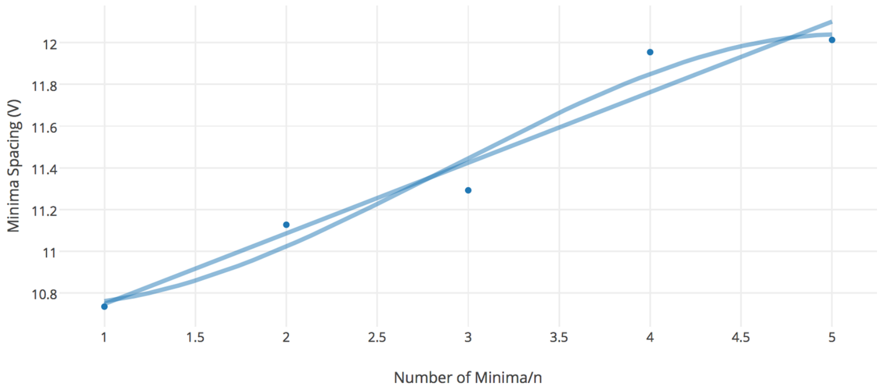

Figure 11.  Spacing between two minima versus the number of minimum for an Argon tube. The error bars are shown. However, since the period was 4ks for the argon experiment, the error bars are very small. There are two different fits for this data: 1) linear fit, and 2) cubic fit.

## Argon Experiment

Using 11 and Eq. 1, we plugged in n=0.5 into the cubic fit to find the lowest excitation energy for argon just like what we did for neon. The number we got appeared to be $10.7991 \pm 0.02$ eV. According to the NIST website, the first excitation energy level occurs around 11.6 eV as shown in 4. 11.6eV does not fall within the range of the experimentally determined lowest excitation level of $10.7991 \pm 0.02$ eV. However, it is close.

## DISCUSSION

The neon experiment seemed to have some sort of systematic error. As mentioned, the first excitation level was suppose to occur around 16.62eV. However, this never happened. And the accelerating voltage went all the way up to 80V, as expected, in our data files. That shows that the applied voltage is not at fault nor are the multimeters. We debugged the circuit to see if we were overloading any part of the circuit, and nothing seemed to be overloaded. There could be a very small extra resistance from the cables used but that would not have a drastic effect of a 3V difference between the actual energy level and the experimental energy level that we observed. So, we conclude that there must have been something wrong with the neon tube. There must have been some sort of extra resistance inside the tube that we did not account for. This could be tested by switching out the tubes; however, we do not have these resources available to us. Therefore, our methods and analysis are correct; however, there seems to be a systematic error with the tube.

As for the argon experiment, the data was more precise. For this part of the experiment, we debugged the whole apparatus and replaced all the equipment. In addition, we used a longer period so there would be more data points. Our methods seem to work out quite well for this experiment. We ended up with an experimental error of 7.4%. Our experimental value seems to lie fairly close to the actual value of the first excitation level for argon.

## CONCLUSION

We studied the Franck-Hertz Experiment, based on our textbook [1], for two different atoms: neon and argon. We found the lowest excitation energy level for neon to occur at $19.4993 \pm 0.6$ eV. Whereas, we found the lowest excitation energy level for argon to occur at $10.7991 \pm 0.02$ eV. The argon data was shown to be the most precise measurements. We conclude that there must have been some systematic error for the neon experiment.

### Derivation

Derivation of Eq. 1:
We have:

$$E_n = n(E_a + \delta_n)$$

$$\delta_n = n\frac{\lambda}{L}E_a$$

Plugging into:

$$\Delta E_n = E_n - E_{n-1}$$

$$\Delta E_n = n(E_a + \delta_n) - (n-1)(E_a + \delta_{n-1})$$

$$\Delta E_n = n(E_a + n\frac{\lambda}{L}E_a) - (n-1)(E_a + (n-1)\frac{\lambda}{L}E_a)$$

$$\Delta E_n = E_a\frac{\lambda}{L}(2n-1) + E_a$$

Therefore, when n=$\frac{1}{2}$:

$$\Delta E_n = E_a$$

In other words:

$$E_a = \Delta E_{(0.5)}$$

[2]

We would first like to thank Dana Parsons for setting up the equipments and guiding us through the lab process. We also would like to express our gratitude to Professor Nat Fortune for helping us when we were confused about our apparatus. Finally, we want to thank Professor Will Williams for helping us to understand the physics behind Franck Hertz experiment.

[1] A. C. Melissinos and J. Napolitano, *Experiments in modern physics.* (San Diego : Academic Press, c2003., 2003).

[2] G. Rapior, K. Sengstock, and V. Baev, Am. J. Phys. **74**, 423 (2006).