Franck-Hertz Experiment: Measuring Transition Energies of Neon and Mercury

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Abstract

By recreating the canonical Franck-Hertz experiment, we showed that energy levels are quantized and measured the energy required to excite neon and mercury atoms. Using an applied voltage varying from 0 - 60 V, we accelerated electrons through a gas of neon atoms, then a gas of mercury atoms to observe the amount of kinetic energy required to excite the atoms. We measured the electron current reaching the anode. As we increased the magnitude of the accelerating voltage we saw the electron current reaching the anode decrease to a minimum at evenly spaced intervals. The drops in the electron current were caused by the electron obtaining enough energy, from the accelerating voltage, to cause the neon or mercury atoms to reach an excited state. After colliding inelastically with an atom, the electrons did not have enough energy to reach the anode, resulting the drop in the electron current. By measuring the differences between the minima in the electron current, we were able to determine the excitation energies of neon and mercury. Mercury has an optimal temperature where the number of minima is maximized and their amplitude is still discernible. After determining the optimum temperature range with direct measurements of the electron current, we used a lock-in detector to get more precise measurements of the minima.

We calculated energy of the transition between states for both neon and mercury. For both neon and mercury, we had to eliminate the effects of the increasing background which can obscure the locations of the minima. After compensating for the increasing background and averaging our data, we found a transition energy for neon of 18.5 $\pm$ 0.4 eV. Our value is in agreement with a large number of transition energies ranging from 18.3 - 18.9 eV. For mercury we found a transition energy of 4.58 $\pm$ 0.24 eV, which agrees with the lowest transition energy of mercury, 4.67 eV.

I. INTRODUCTION

In 1913, Niels Bohr postulated that electrons within an atom can only occupy certain discrete energy levels in his famous Bohr model for atoms. This theory also requires any change in an electron's energy to be discontinuous, equaling to a difference between two of the energy levels. It was not until the next year, 1914, that James Franck and Gustav Hertz provided the experimental evidence to Bohr's energy level postulation. In a vacuum chamber they designed to study the dynamics of the electrons passing through a vapor of mercury, Franck and Hertz observed that a collision between an electron and a mercury atom could result in the electron losing a specific amount of its kinetic energy. The electrons with exactly this amount of kinetic energy were completely decelerated and stopped during the collisions with the atoms, while the faster electrons kept moving forward after the collisions, but lost the same amount of kinetic energy. Slower electrons may collide with the mercury atoms as well, but they did not lose an appreciable amount of kinetic energy. They also discovered that an electron could lose a multiple of this amount of energy when it passed through the vacuum chamber, provided that it is fast enough to endure this loss, or, more specifically, provided it had gained enough kinetic energy in between the collisions.

Franck and Hertz's discovery was consistent with the Bohr model because the collision between an electron (unbound) and a mercury atom could transfer the kinetic energy of the unbound electron to the atom and excite a bound electron inside the atom from the lowest energy level to a higher one. The energy difference between these two energy levels was equal to the kinetic energy loss that occurs to the fast electrons. One should understand that although the Bohr model is regarded as a simplistic and insufficient interpretation of quantum mechanics, its prediction of energy quantization remains true in more advanced models of quantum mechanics.

Later on, Franck and Hertz published another paper about the emissions of light from the atoms that acquired energy from the collider electrons– the excited electron inside the atom decayed into the lowest energy level, emitting a photon with frequency $\nu = E/h$, where E is the energy difference between the two levels, and h is the Planck constant. The kinetic energy absorption and the photon emission jointly demonstrate the quantization of bound electron's energy levels.

Franck and Hertz's apparatus used a glass vacuum tube to contain the gas, and observe

the light emission. A heated filament (cathode) was used to emit free electrons via thermionic emissions. The vacuum tube was heated, so the mercury inside turned into vapor and filled the entire vacuum tube. The vapor pressure of the mercury depends on the temperature, which affects the gas density and the the mean free path for electrons between collisions. There was a control grid, held at a distance from the filament, that was used to create an accelerating voltage. The electric field resulted from this accelerating voltage pulled the electrons towards the grid, and then further to an anode behind the grid to be collected. The anode was held at a voltage slightly negative to the accelerating grid to discourage the electrons that lost their kinetic energy from reaching the anode. Franck and Hertz changed the accelerating voltage and measured the current due to the electrons that reached the anode. They discovered that the current experienced several sharp drops at certain accelerating voltages. The spacings between the voltages of two adjacent drops were always approximately equal– 4.9 V, meaning that an electron lost 4.9 eV of energy every time it collided with a mercury atom and excited a bound electron inside the atom from the ground level to a higher level. Franck and Hertz also discovered that the light emitted from the apparatus had wavelength 254nm, corresponding to exactly 4.9 eV of energy by $\nu = E/h$.

We attempt to reproduce the Franck-Hertz experiment in this lab. We conduct separate experiments with a gas of neon atoms and a gas of mercury atoms. With the modern understanding of the atom's internal energy structure, we are able to find the exact energy level transition involved in the experiment. We use apparatuses similar to that of the original Franck-Hertz experiment, but with some modifications to improve signal-to-noise ratio that will be introduced in the next section. For both neon and mercury, we measure the currents based on varying accelerating voltages. In addition to the original Franck-Hertz experiment, we add temperature control to the apparatus for the mercury atom and study the temperature dependence of the internal transition of the mercury atom. However, in the mercury experiment, we encounter large uncertainties in our results, and to improve our measurements, we implement a lock-in technique for precision measurement of the voltage values where we have sharp drops in current.

II. METHODS

We perform the Franck-Hertz experiment with two types of atoms– neon and mercury. In each setup, we bombard the atoms using electrons whose kinetic energy is controllable. We then can collect the electrons after they pass through the bombardment area, and measure the current due to this collection. The electrons are accelerated by a voltage we can control using a power supply. If we measure the current due to electron collection under different accelerating voltage values, we can find the electrons' final kinetic energy's (after bombardment) dependence on their initial kinetic energy.

A. Neon Gas

We use a glass tube filled with neon gas at room temperature to perform the Franck-Hertz experiment. Figure 1 shows an illustrative diagram of our setup. K is a filament that emits electrons when heated, and it serves as the cathode. The current through the filament is controlled by the power source U_F. We hold this current invariant through out the experiment because it controls the rate of electron emissions, thus any variance in this current could introduce a shift in the final collected current. The current we used to optimize the electron emission rate was 149 mA.

The emitted electrons from the filament may roam freely near the cathode, so we install a grid G in the vicinity of the cathode and apply an initial accelerating voltage to it so that the electrons were drawn towards the grid. The voltage on grid G is held at 2.6 V through a power source U_{KG}. This initial preparation makes sure the emitted electrons are effectively accelerated by the accelerating voltage. Grid A is where the accelerating voltage is applied, by another source U_A, to make electrons acquire kinetic energy in an amount we can control. The accelerating voltage U_A can be set as any value between 0 and 80 V, manually or by ramp control. Ramp control sweeps through the 0-80 V range 60 times a second, which is too fast for the multimeter we use to measure the final current.

It is worth noting that the voltage applied to grid G contributes to the acceleration of the electrons as well, so the total accelerating voltage in the tube is the sum of the two voltages. Behind grid A, there is an electrode serving to collect the electrons flying through grid A. This collector electrode has to be held at a voltage relatively negative to grid A.

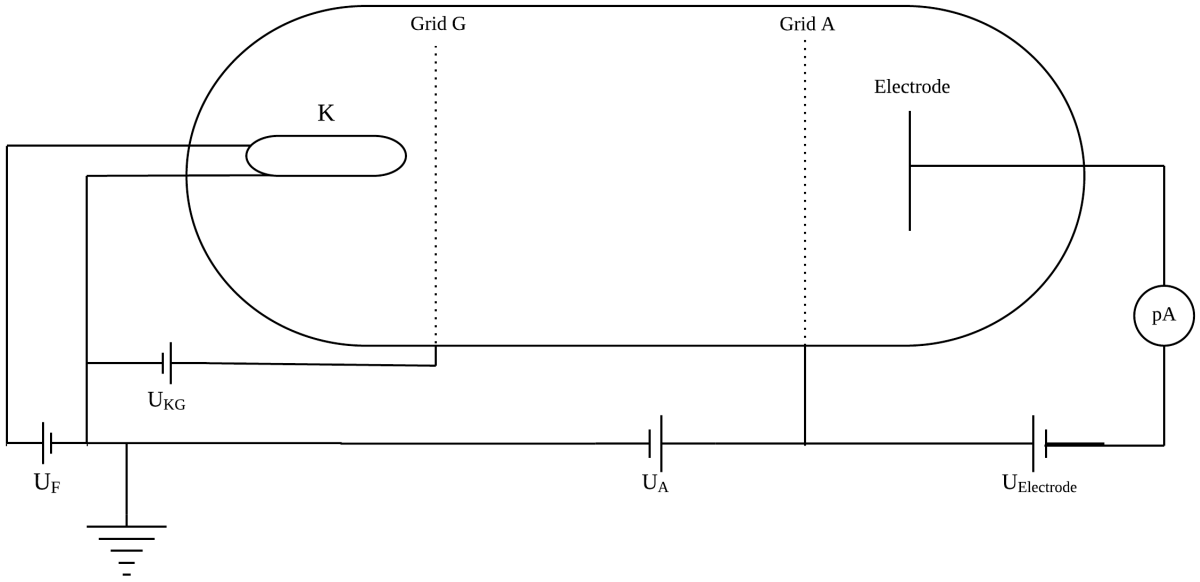

FIG. 1. Experiment setup for the neon sample. Where U_F is the voltage used to current through the filament, K. U_{KG} is the voltage of Grid G and U_A is the voltage of Grid A. $U_{electrode}$ is the retarding voltage.

This way the electrons that lose almost all of their kinetic energy after inelastic collisions with mercury cannot reach the collector, so we can differentiate them better, making the drop in current more observable.

We have one multimeter measuring the accelerator voltage and another one measuring the current through the collector electrode. We control the power supply U_A to increase the accelerating voltage. Initially we attempted to utilize the ramp control to better resolve the change in the current due to the change in the accelerating voltage, but had to give up since the multimeters we used were not capable of effectively responding that fast, given that the 60Hz sweep is a function designed for use with analog oscilloscopes. Instead, we manually controled the accelerating voltage and try to increase it as slowly as possible. The resulting current is plotted versus the accelerating voltage.

B. Mercury Vapor

Performing the Franck-Hertz experiment on mercury requires slight modification to the apparatus. We used a similar glass tube to bombard the mercury atoms with accelerated

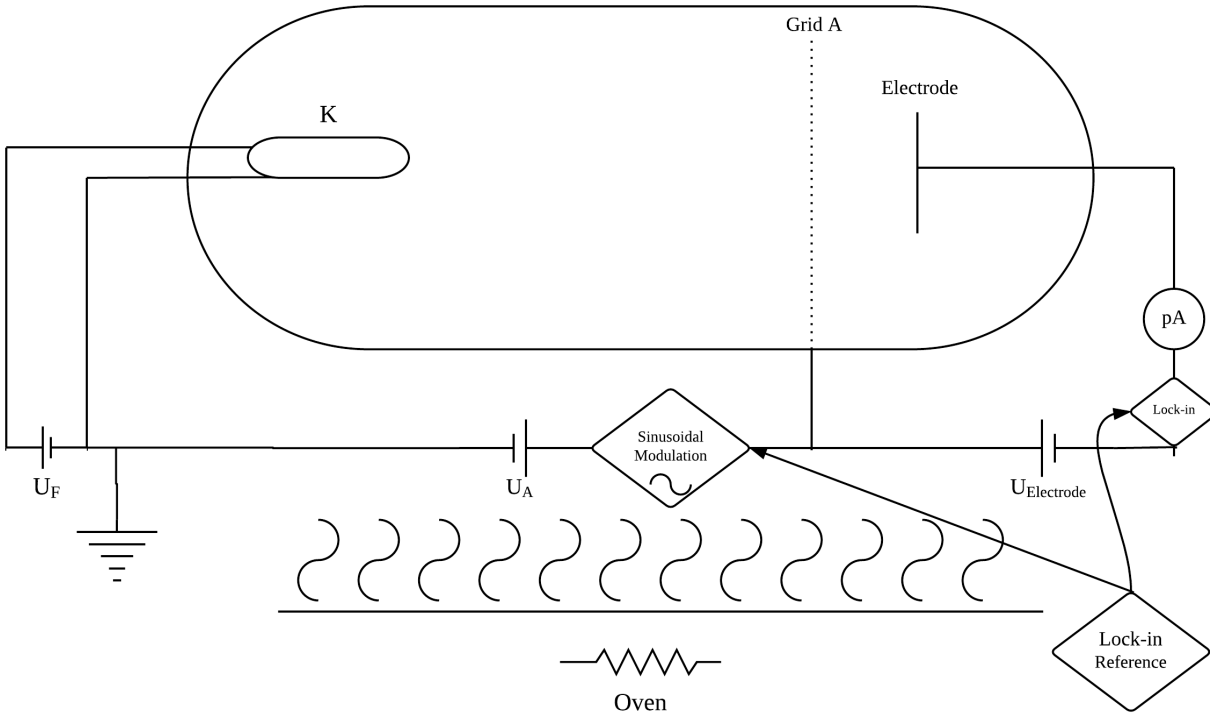

FIG. 2. Experiment setup for the mercury sample. Electrons are emitted from the filament K, then accelerated towards the electrode by the accelerated voltage applied by grid A. U_F is the power supply to generate the constant current through the filament. U_A is the power supply that controls the accelerating voltage. $U_{Electrode}$ is used to the retarding voltage. The diamond containers show the alternative lock-in method.

electrons, but this time the mercury has to be vaporized first. At room temperature, the mercury inside the tube was in its liquid state. To get enough mercury vapor, we needed to heat the glass tube up to a relatively high temperature. We did not have to reach mercury's boiling point as all we needed was a sufficient amount of mercury vapor to be bombarded by the electrons. This requirement in the mercury experiment prompted us to seek the optimal temperature to measure the current's dependence on voltage, so we performed measurements at different temperatures. We used an oven enclosing the whole glass tube to control the temperature.

As seen in Figure 2, the initial accelerating voltage is not present in this experiment. A voltage of 6.5 V is applied to the electron-emitting filament and is held constant throughout the experiment. Like the neon experiment, the current through the filament is constant.

We still use an accelerator grid A to increase the electrons' kinetic energy. This time we can tune between 0 V and 70 V for the accelerating voltage. A retarding voltage of 1.5 V is applied to the collector electrode to serve the same purpose as in the neon example. We will again manually control the accelerating voltage to increase it as smoothly as possible. The results of the two experiments are presented in the next section.

In the mercury experiment, we achieve precision measurement by implementing the lock-in method. The lock eliminates instrumental noises such as power lines from the DC power supply. To do this, we first modulate the accelerating voltage to produce a time-varying sinusoidal signal at the reference frequency and phase. We then feed the final collected current into a lock-in amplifier using the same reference. The output signal is proportional to dI/dV at the particular accelerating voltage. The diamond containers in Figure 2 show where the lock-in method needs to be implemented.

III. RESULTS

A. Neon

We did four data runs using neon. For each run we recorded the accelerating voltage (x data) and the electron current measured by the anode. This current was recorded as a voltage measured across an internal resistor (y data). Each of our runs showed three discernible minima in the voltage corresponding to the electron current. These dips are the voltages just before the electrons have enough energy (from the accelerating voltage) to reach the anode even after an inelastic collision with an neon atom. In an attempt to be concise, we are not showing all of our data, Figure 3 is representative of all the data we collected. The apparent double minima, see the second and third dips in Figure 3, are most likely caused by energy levels with very similar excitation energies.[1] Neon has a band of excitation energies ranging from 18.3-18.9 eV. However, we did not have enough data to determine the individual excitation energies. Also of interest is the voltage corresponding to the steepest negative slope, which is when the majority of electrons have enough energy to excite the neon atoms. However, the location of the steepest negative slope was difficult to determine from our data, as can be seen in Figure 3. We could visually see when the electrons had enough energy to excite the neon atoms by the light emitted by the excited

neon atoms as they returned to their ground state. However we could not determine the individual zones where the neon atoms were excited or the number of times that an electron excited neon atoms.

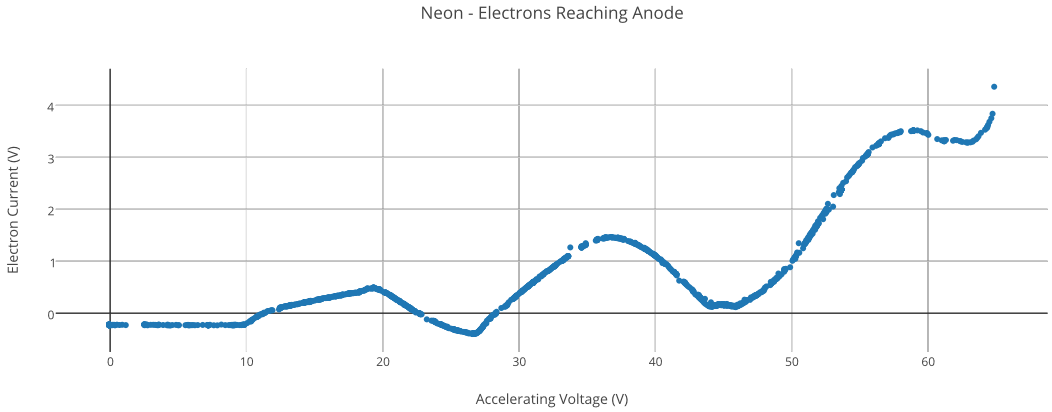

FIG. 3. Neon data with electron current as a voltage plotted against accelerating voltage. The three minima correspond to each electron exciting three neon atoms before reaching the anode. The double minima at the second and third dips are due to the multiple excitation levels with similar energies (degeneracy).

B. Mercury

Since the number of discernible dips for mercury depends on the temperature, we collected data in 10°C increments starting at 150°C and ranging to 210°C. From this data, as shown in Figure 4, it can be seen that there is an optimum temperature at around 200°C at which the most minima can be observed.

Using the information that we obtained about the optimum range of temperature, we took more data using a lock-in detector. The lock-in removed the upward slope in electron current– see particularly 150°C in Figure 4. With the lock-in, we took data from 185°C to 215°C in increments of 5°C. The output from the lock-in, see Figure 5, is the derivative of the direct output without the lock-in. Therefore, the minima in the lock-in output correspond to the steepest negative slope of the direct output and the places the lock-in data pass through zero correspond to the minima and maxima of the direct output. The lock-in detector was highly sensitive to ionization of the mercury atoms. Our 185°C data already

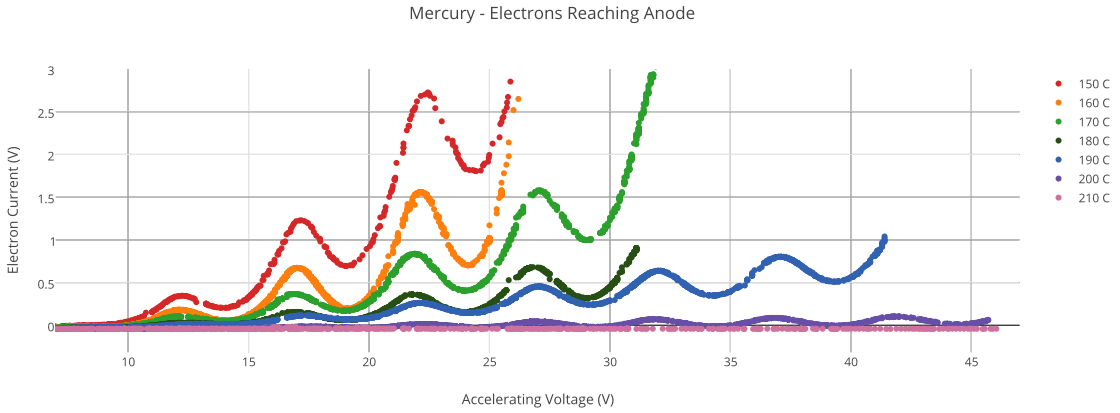

FIG. 4. Mercury data for temperatures ranging from 150°C to 210°C. The range of temperatures shows the optimum temperature to be approximately 190 - 200°C. For higher temperatures, such as 210°C, the minima in the electron current are not discernible. For lower temperatures, for example 150°C and 160°C, there were fewer minima before the mercury atoms are ionized.

showed significant reduction in the number of minima because of ionization, and, at lower temperatures, ionization occurred after only a few minima. Figure 5 is the data collected for 205°C and is a representative sample of the data collected. The data for other temperatures can be seen in the appendix.

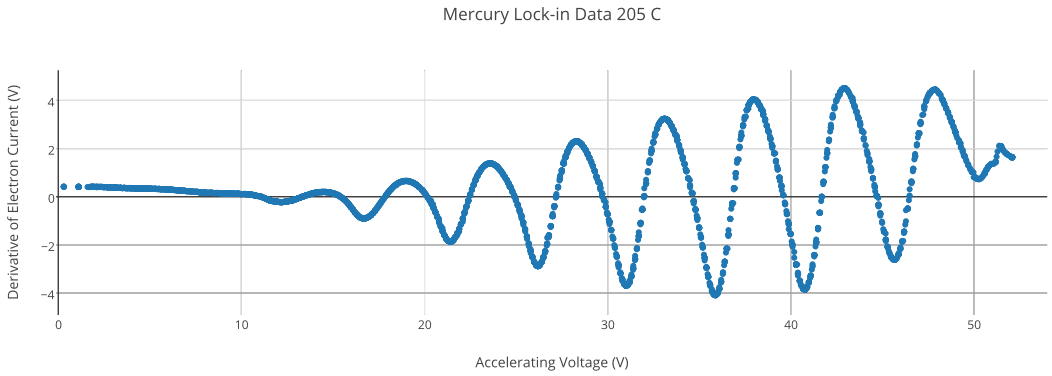

FIG. 5. Sample mercury data at 205°C using the lock-in detector. The lock-in output is the derivative of the direct output in Figure 4. Minima in the voltage correspond to the steepest negative slope of the electron current and the lock-in x intercepts with positive slopes correspond to the minima in the direct output. For all of the data collected with the lock-in, see the appendix.

IV. ANALYSIS

A. Neon

To determine the energy needed to excite the neon atoms, we needed to find the spacing of the minima in the electron current (which we measured as a voltage.) We visually determined the locations of the minima and the steepest negative slopes with uncertainty for each of our data runs– see sample data in Figure 3. We then calculated the changes in voltage between adjacent minima and between adjacent steepest slopes. These values can be seen in Table I.

TABLE I. The differences in voltage for adjacent minima and adjacent steepest negative slopes obtained from all of data runs. Our best value is the average of these values. The large errors are from the difficulty in determining the locations of the minima and steepest slopes.

ΔV Minima	Error ΔV Minima	ΔV Steepest Slope	Error ΔV Steepest Slope
19.0	2.0	19.2	1.5
16.4	2.0	19.5	1.5
18.5	1.3	20.0	2.5
17.6	1.6	18.5	2.5
18.4	1.2	19.5	2.0
17.0	1.5	18.8	2.0
18.5	1.5	18.5	2.5
17.5	2.5	19.5	2.0

We then averaged the first column and got 17.9 $\pm$ .3 eV as the average difference between the minima, where the uncertainty is the standard deviation of the mean. From the difference between the steepest slopes we got an average value of 19.19 $\pm$ .19 eV. We then averaged those two values to get a final value of 18.5 $\pm$ .4 eV, where uncertainty is again the standard deviation of the mean. This value agrees with our expectations because neon has a large number of transitions with energies ranging from 18.3 eV to 18.9 eV.

B. Mercury

Because of the temperature dependence of the mercury data, the process by which we found the energy level was more involved. We began our analysis in a similar way to our analysis of neon by visually determining the location of the minima and steepest negative slope. However, when we calculated the difference in voltage between the minima, this method gave us an uncertainty on the order of 10%. We then plotted the distance between minima versus the minimum number as suggested by Rapior, Sengstock and Baev[1] and fit linear lines to the data for each temperature. Rapior, Sengstock and Baev found that the fit lines from each temperature converged toward the minima number .5. We found that the fit lines to our data did not converge at dip number .5. Furthermore, the uncertainty for our minima was large enough to make our results imprecise and unsatisfying.

To improve our results, we used that data collected using the lock-in detector. Because the lock-in output is the derivative of the direct output, it is the x intercept with a positive slope that corresponds to the minima in the direct data. The minima of the lock-in output correspond to the steepest negative slopes of the direct output. Figure 6 shows the data from the direct output's steepest slope and minima and the corresponding lock-in outputs (minima and positive slope x-intercept) for 200°C. The data with the least uncertainty was the data from the lock-in using the positive x intercepts to calculate the differences in voltage. From this data we found the values seen in Table III and II.

The results of Table II are plotted in Figure 7. The results of Table III are plotted in Figure 8. Following the analysis outlined by Rapior, Sengstock and Baev, we used our fit lines to extrapolate the voltages corresponding to a minima number of .5. Averaging these values gave us 4.46 $\pm$ .12 V, where the uncertainty is the standard deviation of the mean. We repeated this analysis for all lock-in and direct data. The results obtained from all of our mercury data are shown in Table IV. Note the uncertainties for the direct output data are much larger than the lock-in data.

The results in Table IV are very interesting. Both of the values obtained from the direct data are very imprecise and agree with the lowest excitation energy 6^1S_0 to 6^3P_0 (4.67 eV) of mercury and also with the second excitation 6^1S_0 to 6^3P_1 (4.89 eV.)[1]. However, the lock-in data are much more informative. The positive slope x-intercept lock-in data are the most precise values we obtained, but they are no longer accurate. These data do not agree

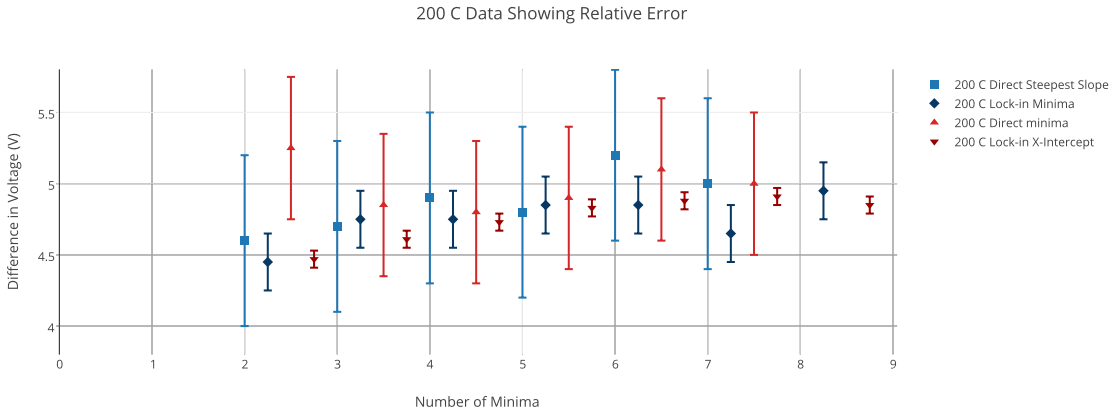

FIG. 6. All the 200°C data with the relative errors. The blue data are the steepest negative slope from the direct data and the corresponding lock-in minima data. The lock-in data have less than half the error of the direct data. The red data is the direct output minima and the lock-in positive x-intercepts. The lock-in positive x-intercepts had the least uncertainty. However, the lock-in intercept data does not agree with the known value of the energy transition– see analysis below.

TABLE II. The difference in voltage for the consecutive minima in the lock-in output corresponding to the steepest negative slope of the direct output. The higher minima of the 185°C data were lost due to ionization. The error for these values is 5%. These values are plotted in Figure 7

Dips	ΔV 215°C	ΔV 210°C	ΔV 205°C	ΔV 200°C	ΔV 195°C	ΔV 195°C	ΔV 185°C
1 - 2	4.40	4.50	4.50	4.45	4.70	4.75	4.80
2 - 3	4.65	4.65	4.70	4.75	4.80	4.80	4.85
3 - 4	4.70	4.75	4.80	4.75	4.80	4.85	4.85
4 - 5	4.80	4.80	4.85	4.85	4.85	4.90	4.90
5 - 6	4.80	4.80	4.85	4.85	4.95	4.90	
6 - 7	4.85	4.85	4.85	4.65	4.95	5.05	
7 - 8	4.80	4.90	4.90	4.95	5.05	5.00	

with the known value of the lowest excitation energy of mercury. These data correspond to the minima of the direct data which have a systematic error. Because of the increasing background, the locations of the minima in the direct data are at lower values. This would be eliminated in the lock-in data if the background increased linearly, but our data suggest

TABLE III. The difference in voltage for consecutive positive slope x-intercepts from the lock-in output corresponding to the minima in the direct output. The first dip was indiscernible for the 215°C data and the higher minima of the 195°C and 185°C data were lost due to ionization. The error for these values is 1.3% and they are plotted in Figure 8

Dips	ΔV 215°C	ΔV 210°C	ΔV 205°C	ΔV 200°C	ΔV 195°C	ΔV 195°C	ΔV 185°C
1 - 2		4.67	4.53	4.42	4.36	4.58	4.51
2 - 3	4.63	4.57	4.63	4.61	4.63	4.78	4.82
3 - 4	4.67	4.69	4.63	4.73	4.84	4.87	4.90
4 - 5	4.74	4.79	4.89	4.83	4.87	4.93	
5 - 6	4.76	4.80	4.87	4.88	4.95	4.99	
6 - 7	4.76	4.82	4.84	4.91		5.05	
7 - 8	4.76	4.73	4.77	4.85		4.90	

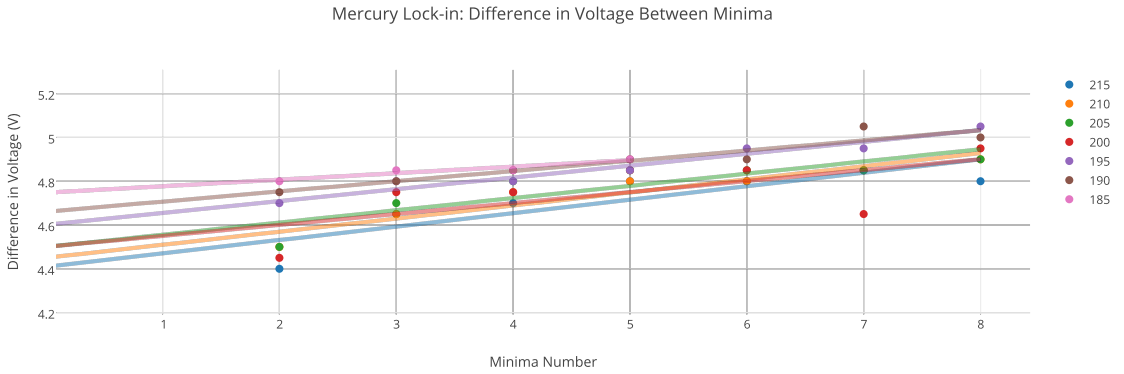

FIG. 7. The plot of the difference in voltage between minima versus the number of the minima from the lock-in data. These values correspond to the steepest negative slope of the direct output. All values have an uncertainty of 5%. The lines are linear fits to the data for each temperature.

that the background increases faster than a linear model because the lock-in value shows the same systematic error. In Table IV, it can be seen that the value from the x-intercept lock-in data is much lower than the other values.

To eliminate this problem, we used that the data from the steepest negative slope direct output and the corresponding lock-in minima data. Using the lock-in minima, we were able to get a value that is both precise and accurate. The lock-in minima value, 4.58 ± 0.24

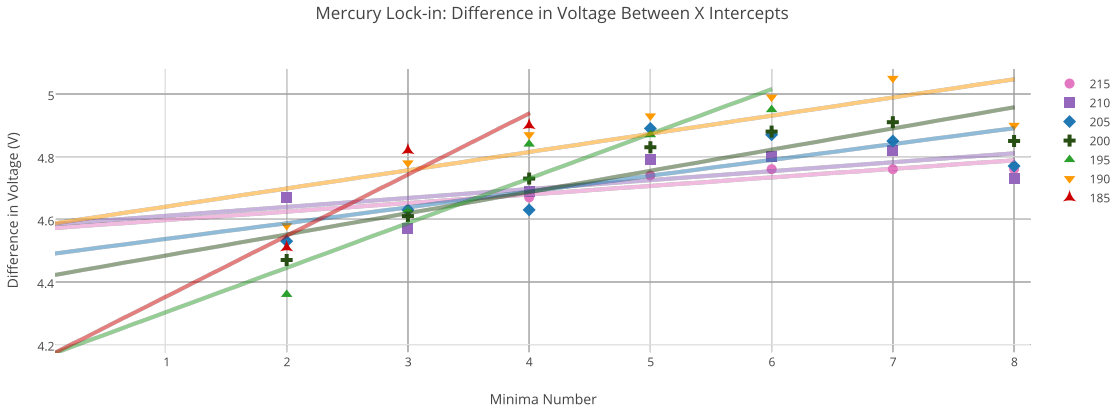

FIG. 8. The plot of the difference in voltage between positive-slope x intercepts versus the number of the minimum. These value correspond to the minima of the direct output. All values have an uncertainty of 1.3%. The lines are linear fits to the data for each temperature. The two fits with steeper slopes correspond to the 195°C and 185°C data sets, which were truncated due to ionization.

TABLE IV. A summary of the best values and uncertainties from each of our data sets. All of these values, except the lock-in positive x-intercept value, agree with the expected energy value for mercury transitions.

Direct Steepest Slope	Lock-in Minima	Direct Minima	Lock-in Positive Slope X-Intercept
4.6 ± 0.7 eV	4.58 ± 0.24 eV	4.6 ± 0.4 eV	4.46 ± 0.12 eV

eV, is in agreement with the lowest excitation energy of mercury (4.67 eV). Furthermore, the lock-in minima value is only in agreement with that one excitation energy, not with the second excitation energy of 4.89 eV.

V. DISCUSSION

All of our data were consistent with our expectations based on theory and past experiments. We were able to see the drops in the electron current at regular intervals as electron gained enough energy to excite the neon or mercury atoms. For mercury, we saw that there was an optimal temperature range when drops in the electron current were maximized in number and still discernible in amplitude. As suggested by Rapior, Sengstock, and Baev,

the difference in voltage between our minima tend to increase as the number of the minimum increases.

One of the biggest limitations in our experiment was our uncertainty in the precise voltages corresponding to the minima and steepest slopes. Particularly for the lock-in data, but also for the direct data, our uncertainty was largely based on the resolution of our graphs. The direct output data used a power supply with a resolution of 0.1 V. For the lock-in data, we used an independent power supply that also increased the accelerating voltage in increments of 0.1 V. These increments of 0.1 V gave us an uncertainty on that order of magnitude and set a lower limit on our uncertainty. If we had increased the accelerating voltage in increments of 0.01 V, we would have had a better resolution of our data and less uncertainty in our analysis.

VI. CONCLUSION

18.5 $\pm$ 0.4 eV, the value we got for the neon excitation energy, is in agreement with a large number of excitation energies for neon between 18.3 - 18.9 eV. We were not able to determine the energy transitions more precisely from the data we collected. With our apparatus, we were only able to obtain three minima before the neon ionized. Using different instrumentation, we might be able to obtain more data and calculate the transition energy more precisely.

Our final value for mercury energy transitions was 4.58 $\pm$ 0.24 eV, which agrees with the known value for the lowest energy transition, 4.67 eV. We obtained this value from the minima of the lock-in data.

To make our best value for the mercury transition energy more precise, we would need a more sensitive measurement of the electron current. Then we could have seen more minima below the first minima that we could detect. Having more minima would increase the number of data points used to fit lines and extrapolate the transition energy. Since some of our fit lines were made with only a couple of data points, increasing the number of points would help average out outliers that are indiscernible with only a few points.

As Franck and Hertz first found, this experiment clearly shows that electrons must have a certain quantified amount of energy before they can excite atoms. This result supports the premise of quantum mechanics and makes an abstract theory more tangible.

VII. APPENDIX

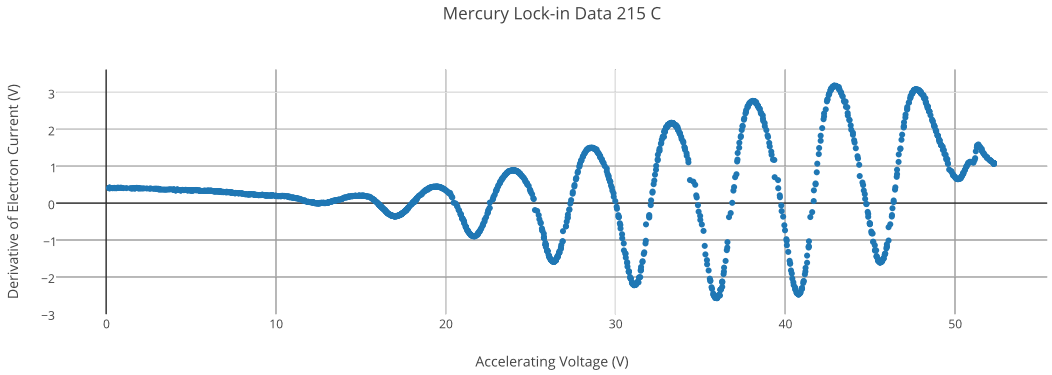

FIG. 9. Mercury data collected using the lock-in at 215°C.

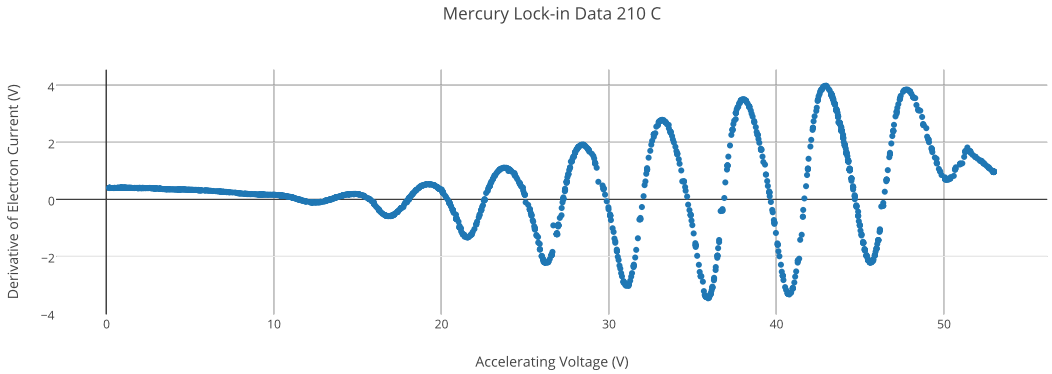

FIG. 10. Mercury data collected using the lock-in at 210°C.

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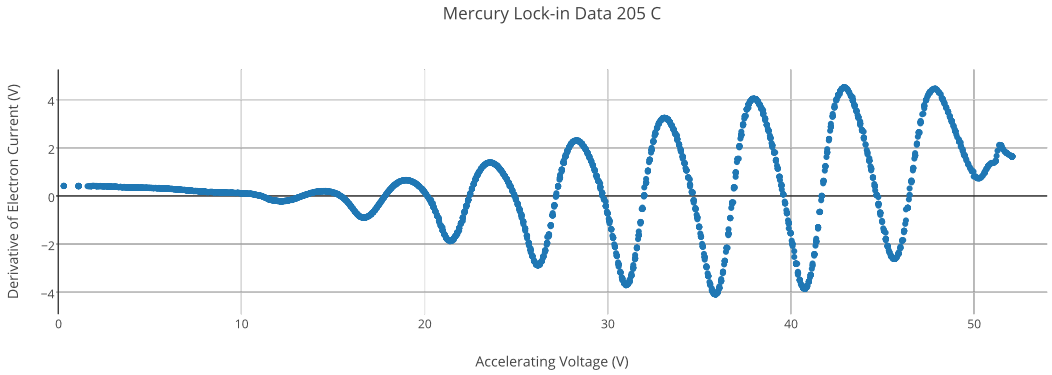

FIG. 11. Mercury data collected using the lock-in at 205°C.

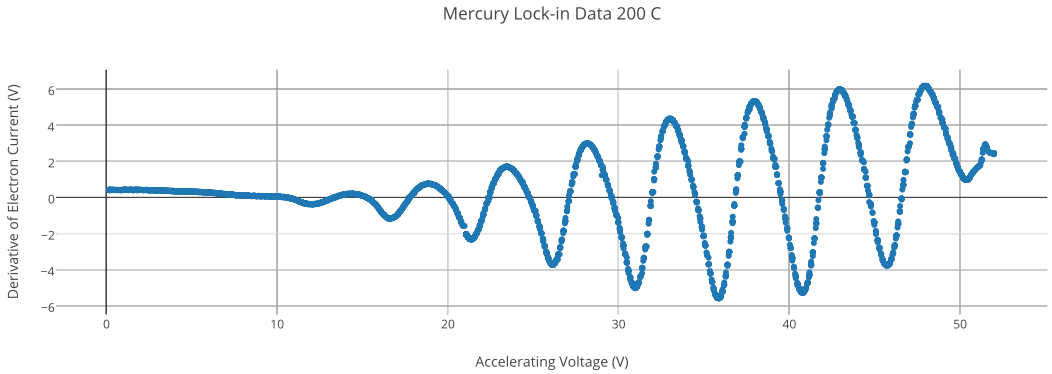

FIG. 12. Mercury data collected using the lock-in at 200°C.

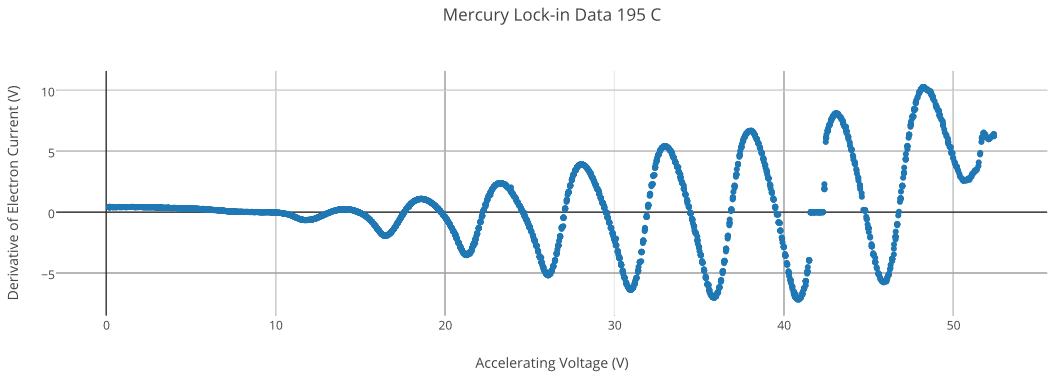

FIG. 13. Mercury data collected using the lock-in at 195°C.

[3] Hyper-Physics: Franck-Hertz Experiment Website <http://hyperphysics.phy-astr.gsu.

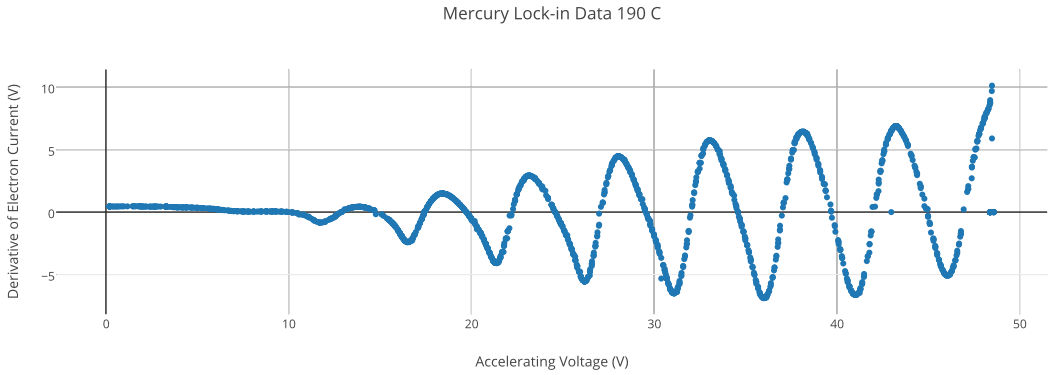

FIG. 14. Mercury data collected using the lock-in at 190°C.

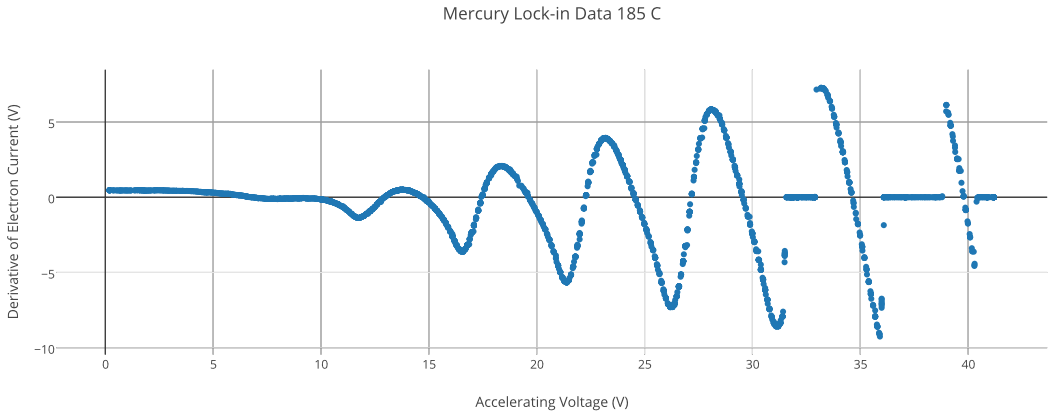

FIG. 15. Mercury data collected using the lock-in at 185°C. Note the ionization at high accelerating voltages

edu/hbase/frhz.html>