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

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Abstract

We recreated the canonical Franck-Hertz experiment and measured the energy required to excite neon and mercury atoms. Using a voltage we accelerated electrons through a gas of either neon or mercury atoms. We measured the electron current reaching the anode. As we increased the magnitude of the accelerating voltage we saw the number of electrons reaching the anode decrease to a minimum at evenly spaced intervals. The drops in the electron current were caused by electron obtaining enough energy, from the accelerating voltage, to cause the neon or mercury atoms to reach an excited state. After the colliding inelasticity with an atom the electrons did not have enough energy to reach the anode resulting the drop in electron current. By measuring the difference between the minima in the electron current we were able determine the excitation energy of neon. Mercury has an optimal temperature were the number of minima is maximized and their amplitude is still discernible. After determining the optimum temperature range with direct measurements of electron current, we used a lock-in detector to get more precise measurements of the minima. We plotted the difference in energy against the number of the minimum and used fit lines to extrapolate to a minimum number of .5. Averaging all of our data we got excitation energy for neon of 18.5 $\pm$ .4 V and for mercury of 4.58 $\pm$ .4 V. Our results for both mercury and neon agree with the expected values for the excitation energies of neon and mercury. However neither of our values were precise enough to correspond to a single excitation energy because of the resolution of our instruments.

I. INTRODUCTION

The Franck-Hertz experiment was one of the seminal experiments supporting quantum mechanics. Quantum mechanics postulates that atoms do not have continuous energy profiles, that there are only certain specific energies that an atom can have. Franck and Hertz showed this by passing electrons through a gas of atoms.

II. METHODS

A. Neon

B. Mercury

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 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 a neon atom. In an attempt to be concise we are not showing all of our data, Figure 1 is representative of all the data we collected. The apparent double minima, see the second and third dips in Figure 1, is most likely caused by by energy levels with very similar excitation energies.[1] Also of interest is the voltage corresponding to the steepest negative slope which is when the majority of electrons have enough energy to cite the neon atoms. However the location of the steepest negative slope was difficult to determine from our data as can be seen in Figure 1.

B. Mercury

Since the number of discernible dips for mercury depends on temperature, we collected data in 10°C increments starting at 150°C and ranging to 210°C. From this data, see Figure 2,

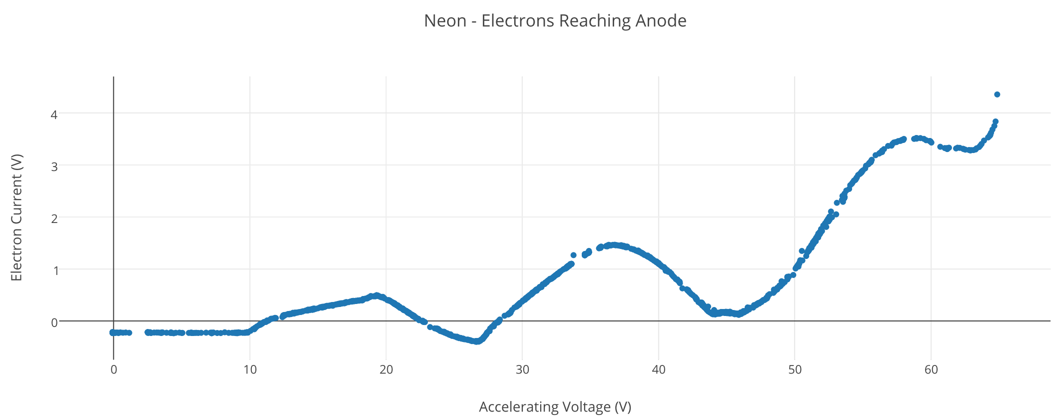

FIG. 1. Neon data with electron current as a voltage plotted against accelerating voltage. The three minima correspond to each electron exciting three neon atoms before reaching the anode. The double minima in the second and third dips is due to multiple excitation levels with similar energies.

it can be seen that there is an optimum temperature at around 200°C at which the most minima can be observed.

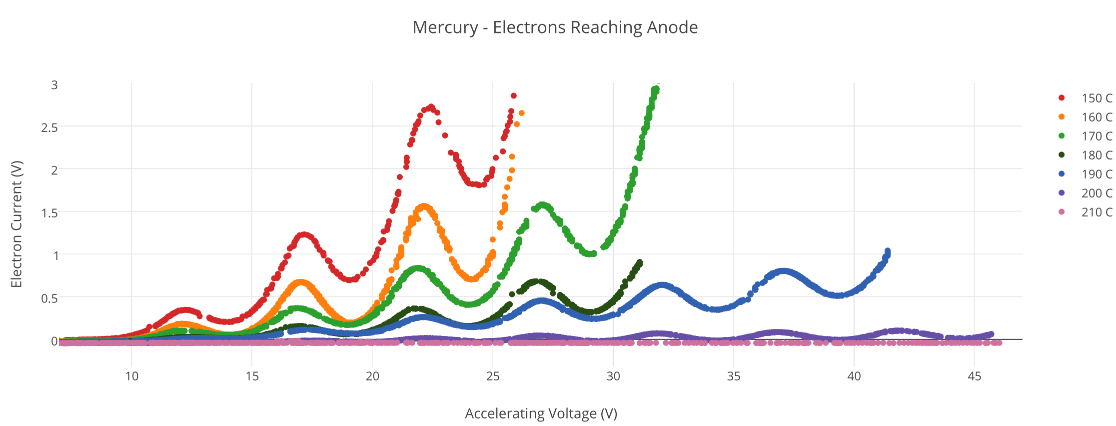

FIG. 2. Mercury data for temperatures ranging from 150°C to 210°C. The range of temperatures shows the optimum temperature to be approximately 190 - 200°C. For higher temperatures, such as 210°C, the minima in electron current are not discernible. For lower temperatures, for example 150°C and 160°C, there were fewer minima before the mercury atoms are ionized.

Using the information that we obtained about the optimum range of temperature, we took a more data using a lock-in detector. The lock-in blocked the upward slope in electron current, see particularly 150°C in Figure 2. 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 3, 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 passes 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 showed significant reduction in the number of minima because of ionization. Because of space considerations we are not showing all of our lock-in data. Figure 3 is the data collected for 205°C and is a representative sample of the data collected.

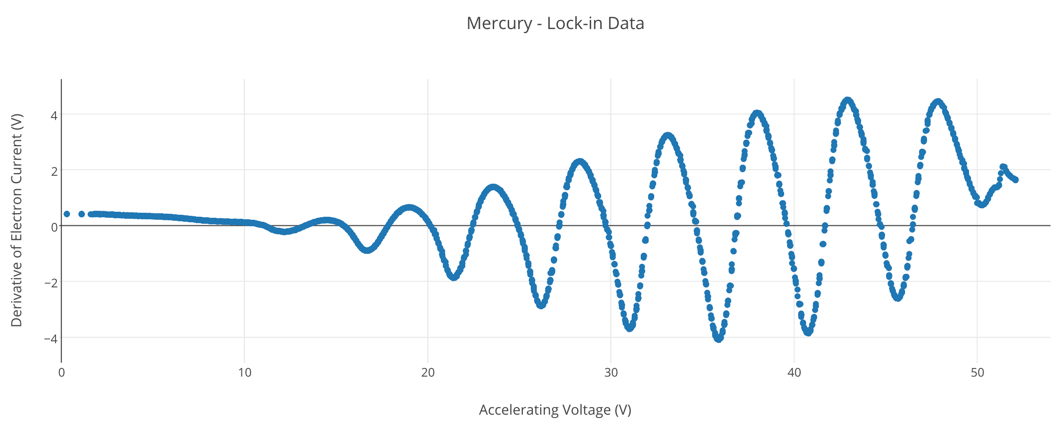

FIG. 3. Sample mercury data at 205°C using the lock-in detector. The lock-in output is the derivative of the direct output in Figure 2. Minima in the voltage correspond to the steepest negative slope of the electron current and the lock-in x intercepts with positive slopes correspond to the minima in the direct output.

IV. ANALYSIS

A. Neon

To determine the energy needed to excite the neon atoms we needed to find the spacing of the minima in 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 1. We then calculated the change in voltage between adjacent minima and between adjacent steepest slopes. These values can be seen in Table I.

TABLE I. The difference 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 location of 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 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 and the minima of the lock-in output corresponds to the steepest negative slopes of the direct output. Figure 4 shows the data from the direct output 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 that 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 II.

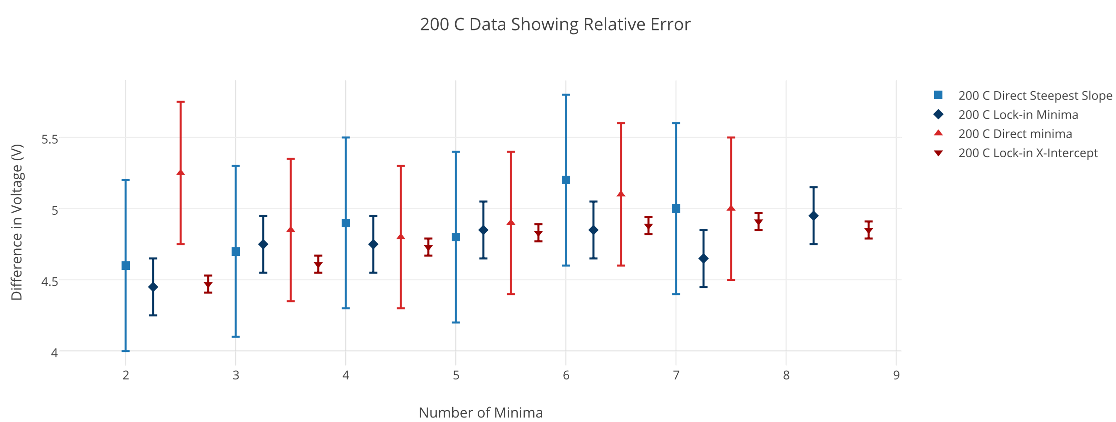

FIG. 4. All the 200°C data shown with the relative errors. The blue data is the steepest negative slope from the direct data and the corresponding lock-in minima data. The lock-in data has less than half the error of the direct data. The red data is the direct output minima and the lock-in positive x-intercepts. The lock-in positive x-intercepts had the least uncertainty.

The results of Table II are plotted in Figure 5. Following the analysis outlined by Rapior, Sengstock and Baev, we used our fit lines to extrapolate to the voltages corresponding to a minima number of .5. Averaging these values gave us 4.46 ± .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 in Table III, note the much larger uncertainties for the direct output data than the lock-in data.

Averaging the best values from each set of data, from Table III, we got a final value of 4.56 ± .4 V. This value agrees with the known value of the lowest excitation 6^1S_0 to 6^3P_0

TABLE II. The difference in voltage for consecutive positive slope x-intercepts in from the lock-in 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%

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	

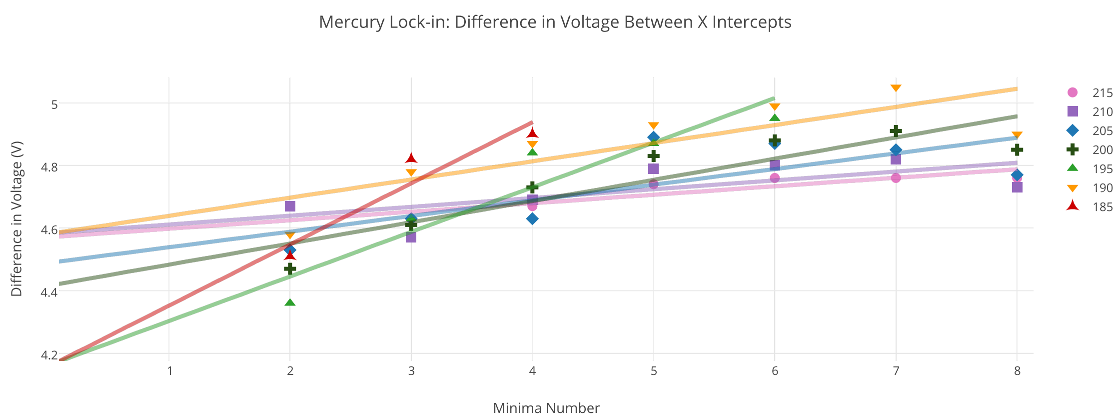

FIG. 5. The plot of the difference in voltage between minima versus the number of the minimum. All values have an uncertainty of 1.3%. The lines are linear fits to the data for each temperature. The two fits with steeper slopes correspond to the 195°C and 185°C data sets which were truncated due to ionization.

(4.67 eV) of mercury and also with the second excitation 6^1S_0 to 6^3P_1 (4.89 eV.)[1]

TABLE III. 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	4.58 ± 0.24 V	4.6 ± 0.4	4.46 ± 0.12 V

V. DISCUSSION

All of our data was consistent with our expectations based on theory and past experiments. We were able to see the drops in 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 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 tended to increase as the number of the minimum increased.

Our final values for the energy needed to excite mercury show a stark trade off of accuracy versus precision. Our direct data values have a very large uncertainty (10 - 15%), see Table III, so they are not very precise, but they are accurate. Whereas our lock-in x-intercept data has a much smaller uncertainty (2.7%) a much higher precision, but it is no longer accurate because it is not in agreement with the known value of the excitation energy.

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 the power supply that came with the apparatus, it had 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 better resolution of our data and less uncertainty in our analysis.

VI. CONCLUSION

18.5 % .4 V, 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 V. We were not able determine the energy transitions more precisely from the data that 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 more precisely.

Our final value for mercury energy transitions was 4.56 $\pm$ .4 V which agrees with the known values for both the lowest energy transition, 4.67 eV, and the next lowest energy transition, 4.89 eV. We would hope for a more precise answer that would correspond with just one of the energy transitions. However, the resolution of our data was restricted by the apparatus we used.

It is possible that a most sensitive measurement of electron current 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 to average out outliners that are undiscernable with only a few points.

Despite our difficulty in precisely determining the excitation energy of mercury, the overall results of this experiment are still as fascinating as they were for Franck and Hertz. 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.

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[1] Gerald Rapior, Klaus Sengstock, and Valery Baev, "New Features of the Franck-Hertz Experiment," Am. J. Phys. **74**, 423–428 (2006).

[2] Adrian C. Melissanos and Jim Napoitano, *Experiments in Modern Physics* 2nd edition (Academic Press, Boston, 2003).

[3] Hyper-Physics: Franck-Hertz Experiment Website <http://hyperphysics.phy-astr.gsu.edu/hbase/frhz.html>