Franck-Hertz Experiment

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Abstract

The Franck-Hertz experiment demonstrates the quantum nature of atoms: the energy levels are discrete. In this experiment, electrons generated at the cathode are accelerated to increasing energies and sent through an atomic gas. The current of electrons reaching the anode (converted to a voltage) is measured. Since the atoms can only gain discrete amounts of energy, there will be dips in the current, corresponding to the electrons transferring all their energy to the atoms, and subsequently unable to reach the anode. By looking at the spacing of dips in the data, one can determine the transition energies of the atom. We performed the Franck-Hertz experiment with neon and mercury gas, with the mercury at various temperatures. We also performed the experiment with mercury at 204°C using a lock-in amplifier by adding small sinusoidal oscillations on top of a relatively larger voltage used to accelerate the electrons. We visually estimated the minima locations and uncertainties from the plots. This gave better results compared to using curve fits to determine the minima. We obtained an estimate of 4.76 ± 0.10eV for the lowest excitation energy of mercury from our minima spacing data. This lies between accepted values for the first two transition energies of mercury, 4.67eV and 4.89eV, but agrees with only the first one.[1] We think the discrepancy is caused by the lack of control in accelerating voltage, which made it difficult to take data points at small, consistent intervals, and so accurately determine minima. We think finer control of the accelerating voltage would allow us to collect better data, leading to more defined minima, allowing us to more accurately determine the lowest excitation energy of mercury.

I. INTRODUCTION

The Franck-Hertz Experiment is named for James Franck and Gustav Hertz, who used it to demonstrate discrete energy levels in atoms. They received the Nobel Prize in 1925 for their work on this experiment. In the experiment a beam of electrons is sent through a cloud of atoms, usually mercury or neon. Atoms can only gain energy in an amount equal to an allowed transition between energy levels. Only electrons with energies equal to these transition energies can transfer their energy to an atom. Electrons that have too much or too little energy will collide elastically with the atoms, keeping their energy. We find the transition energies by measuring the current of electrons leaving the gas - fewer reach the detector when they transfer energy to atoms in collisions. The loss in energy keeps those electrons from overcoming the retarding voltage at the anode. This causes dips (minima) in the current at voltages where many electrons can reach a transition energy one or more times during their journey through the gas. The spacing of the minima (in volts) gives the energy (in electron-volts) that colliding electrons gain between collisions - assuming the electrons lose all their energy in collisions. The next minimum occurs when the electrons gain back just enough energy to collide and lose their energy again. This energy gain - from zero to collision energy - is a transition energy of the atom. In this way the Franck-Hertz experiment can be used to determine the transition energies of the atom. Further research on the Franck-Hertz experiment in Mercury has shown a temperature dependence of the minima spacings, and examined how the minima spacings increase slightly at higher voltages. In our analysis we investigated temperature dependence briefly to chose a temperature at which the pattern in the data was most clearly defined, and we used the expected increase in minima spacing with voltage to better estimate the actual transition energy occuring in the gas.

II. METHODS

For this experiment we used a Franck-Hertz experimental apparatus from ELWE. A diagram is shown in Figure 1. First, we heat the oven containing the glass tube with mercury gas to the desired temperature. (In the diagram the part of the apparatus conatined in the oven is shaded grey.) Next, a filament with 120 mA of current creates a cloud of electrons inside the mercury gas. We set the filament voltage by placing an ammeter in line between

the control box and the filament, then raising the filament voltage until the meter stabilized at 120mA. Inside the gas, a potential difference (which we call the accelerating voltage) drives the electrons through the apparatus. The voltage is applied to a grid inside the gas - it attracts the electrons but allows them to pass through it, eventually reaching the anode. We can control the energies of the electrons by varying the accelerating voltage. Electrons which have transferred energy in collisions have less energy at the other end of the apparatus, and a retarding potential prevents these electrons from reaching the anode. We set the retarding potential at 5 V. The current at the anode is converted to a voltage by the apparatus - the current runs through a resistor inside the control box, and the control box has an output which is the voltage across that resistor. This voltage is our output voltage. To take data, we slowly increased the accelerating voltage from zero until the gas began to ionize, and measured the output voltage from the anode.

We performed this experiment with neon gas and mercury gas. The neon experiment yielded poor data: we could only discern two peaks, and their shapes were irregular. Therefore, we took the bulk of our data with mercury. The mercury gas experiment was performed with gas temperatures from 170°–210°C. Then was done so we could select an optimum temperature at which to take data with the lock-in. We decided on 204 °C.

For direct measurements, we connected the accelerating voltage from the control box to a multimeter, and the output voltage to another multimeter. With the computer, we plotted accelerating voltage versus output voltage. The procedure for using the lock-in was more complicated. We used a function generator to add a periodic voltage on top of the accelerating voltage supplied by the control box. We then connected the reference from the function generator and the output voltage to the lock-in detector, and the resulting signal went to the second multimeter in place of the unmodified output voltage. Using the lock-in had the effect of taking the derivative of the orignal data - the minima locations changed, as did the shape of the peaks and dips. However, the spacing between the minima of the lock-in data had the same period as the original data: taking the derivative of a periodic funciton does not change its period. Therefore we used the minima spacing from both the direct data and the lock-in data to try and extract the transition energy.

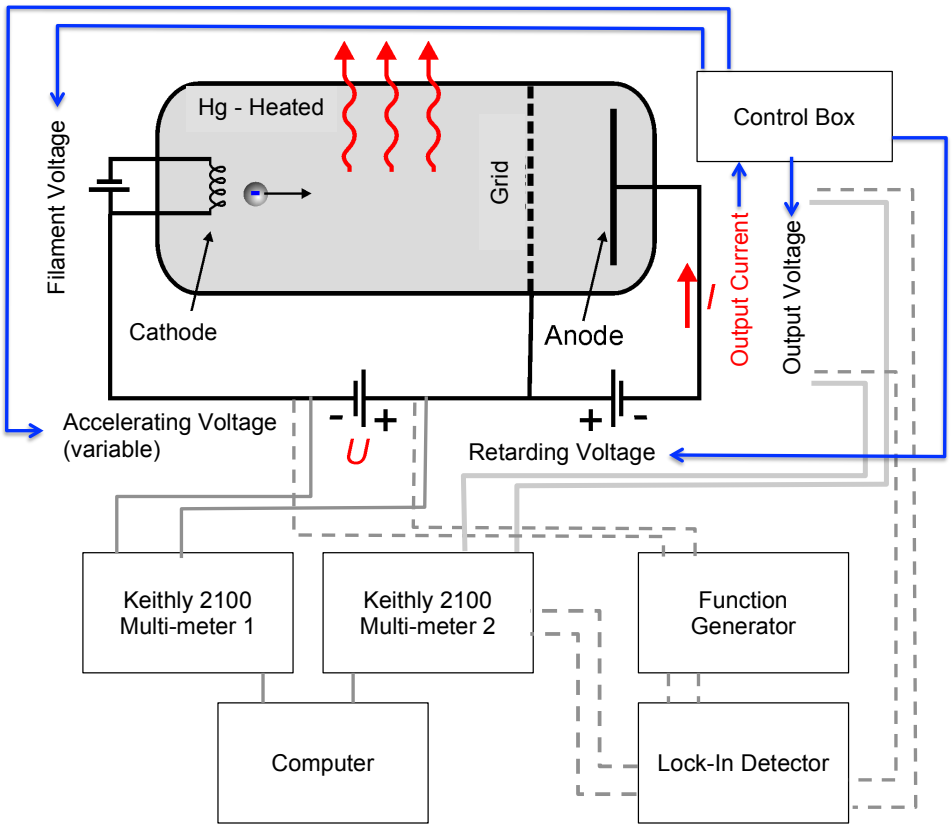

FIG. 1. The ELWE experimental apparatus, with the connections used to take measurements using both the direct method and the lock-in method. The apparatus consists of a control box (supplying the filament voltage, accelerating voltage, retarding voltage, and output voltage) and an oven, inside of which is the cloud of heated gas, the filament, the grid, and the anode. The solid lines, light and dark grey, show the instrument connections for direct measurements. The dark grey lines, dashed and solid, show the instrument connections for the lock-in measurements.

III. RESULTS

Figure 2 shows our data for mercury gas at various temperatures. At lower temperatures, the output voltage values rose more quickly, and ionization voltage (where we stopped taking data) occured at lower values of accelerating voltage. At high temperatures the output voltage values rose slowly, so we could record more peaks before ionization, but the earlier peaks were shallower and less well defined. The connection between temperature and rate of increase is the mean free path of the gas. At lower temperatures, the gas is less dense. Thsi means that an electron is more likely to travel further between collisions with atoms

- the "mean free path" is this distance. A longer path between collisions means the atom has more time to gain energy as the accelerating voltage propels it through the gas, and so it has more "extra" energy between collisions. Therefore the electrons which reach the anode have more "extra" energy as well, which causes an increase in the entire dataset - a background. The magnitude of the background is temperature dependent.

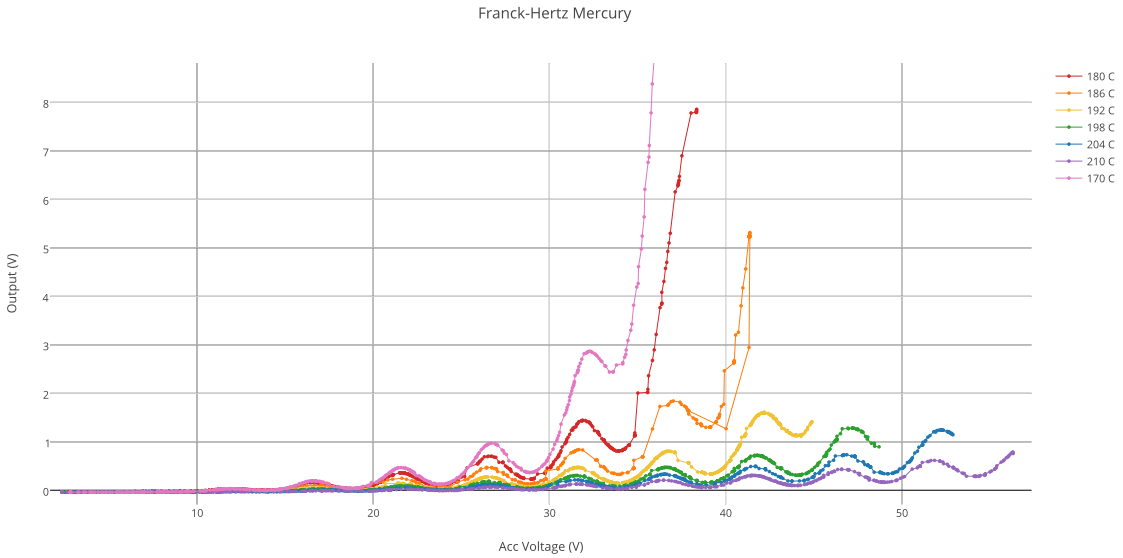

FIG. 2. A plot of the measured output voltage as a function of accelerating voltage for various temperatures of mercury gas. The general background trend flattens as the temperature increases.

After comparing the curves, we decided that the data for 204 °C (the blue curve in Figure 2) had the most minima without losing the first few to the decreasing amplitude. Figure 3 shows our data with a polynomial background fit.

We also took data by the lock-in method, shown in Figure 5 in the Analysis section with the background subtracted.

IV. ANALYSIS

Since we only saw two dips in our neon data, we did no further analysis it. Our mercury data was imported into Igor Pro. Most of our analysis was performed on data at 204°C. We first fit a background curve to both the data using the lock-in and the data without so it can be removed. It is easier to determine the minima without the background present.

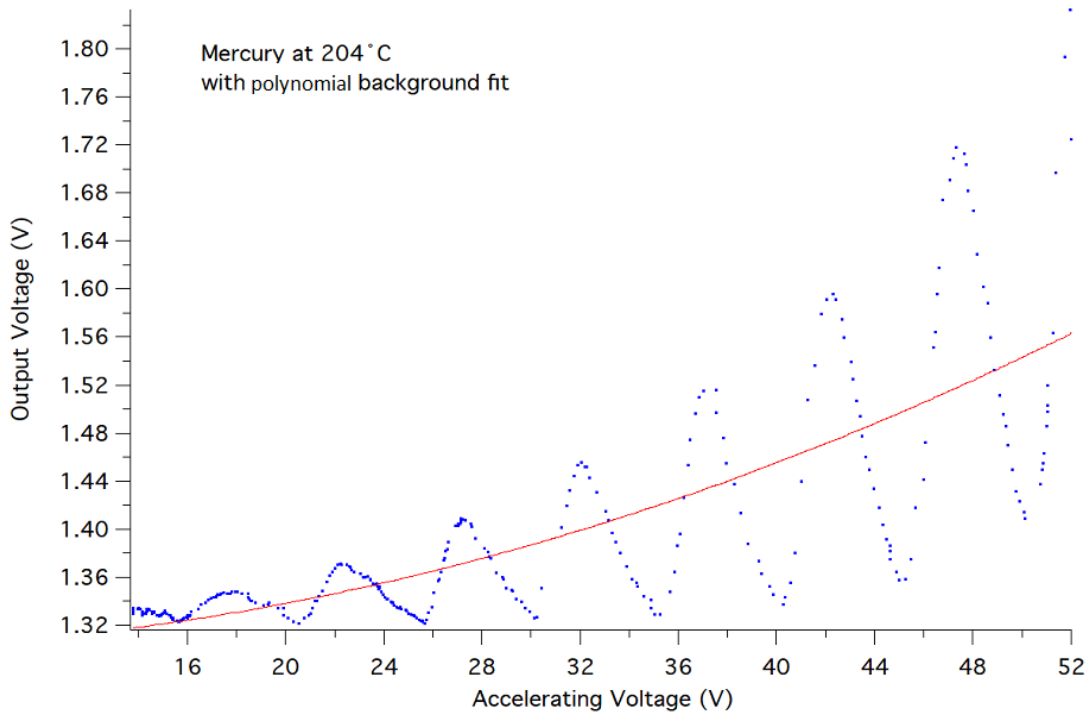

FIG. 3. A plot of the measured output voltage as a function of accelerating voltage for mercury gas at 204 °C. The general background trend is shown as a polynomial fit to the whole dataset.

The background is a due to electrons which gain energy between collisions, and still have that extra energy when they reach the anode. At higher values of accelerating voltage the electrons gain energy more quickly, so the background is larger. Likewise, at lower temperatures the gas is less dense, and so the electrons have a longer time between collisions in which to gain energy, which also increases the background. This is why the background of the graphs for lower temperatures increases more quickly. This increase is not related to the transition energies of the gas - in fact, the background distorts the dips in the data and shifts their lowest point slightly. Therefore, an accurate measure of the minima needs to be taken with the background subtracted. The background curves were fitted using trial and error; we picked the one that best split the oscillations of the output voltage into equal amplitudes above and below the background. Fig. 4 and 5 show the output voltage with the background removed.

The minima for the data without the lock-in look parabolic while those of the lock-in data look linear. We performed linear fits on each side of the minimum for the lock-in data. The intersection of these lines was our estimate of the minimum. The curve fitting was done using

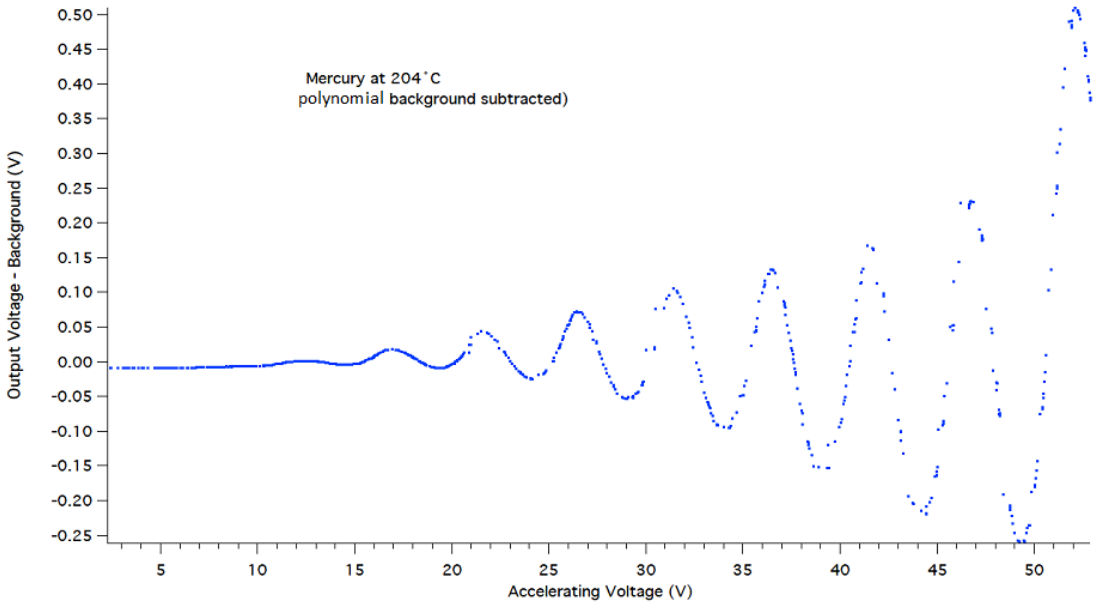

FIG. 4. A plot of the output voltage minus the background for mercury at 204°C.

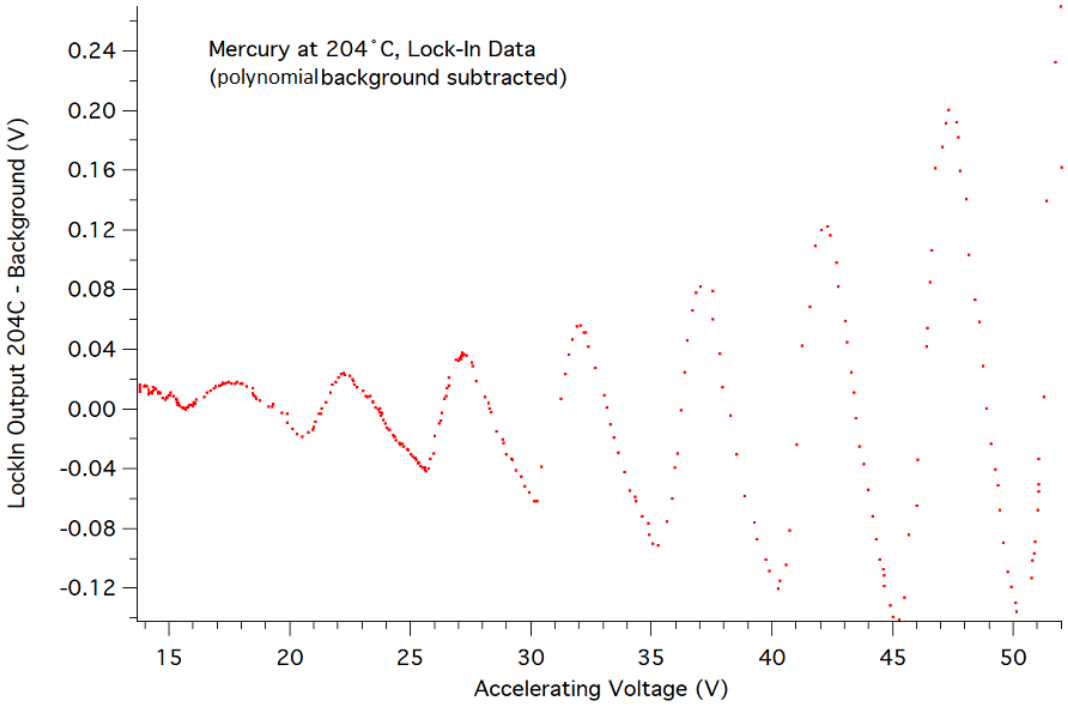

FIG. 5. A plot of the output voltage minus the background using the lock-in for mercury at 204°C

Mathematica, as the uncertainties in the minima from curve-fitting in Igor Pro were larger than the range we fit the data over, thus they were not a accurate measure of our uncertainty

in determining the minima. We determined our uncertainty by first altering the slope and intercept of the best-fit line determined by Igor Pro, such that the line was no longer a good fit to the data. We obtained high and low values of the slope and intercept. Thus our uncertainty in the slope and intercept values was half of the difference between the high and low values. Finally, the uncertainty in our minimum was determined by propagating the slope and intercept errors. Although this method reduced the uncertainty relative to that from Igor Pro, the range of values for each minimum was still larger than what it appears to be looking at the data. Additionally, some values of the minima did not appear to match when we compared it to our data by eye. At this point, we decided to use the old-fashioned method of estimating our minimum by eye as well as the uncertainty for our both sets of data. Then we calculated the spacing between successive minima (Table I and Fig. 6).

The spacings should increase linearly with the number of minima, due to extra acceleration of the electron before it collides with an atom. The expected spacing between minima is given by

$$\Delta E(n) = E_n - E_{n-1} = \lfloor 1 + \lambda/L(2n-1) \rfloor \, E_a, \tag{1}$$

where λ is the mean free path of the electron (the average distance it moves before colliding), L is the anode to cathode distance, and E_a is the lowest excitation energy of the atom. The lowest possible excitation energy from Eq. 1 is $E_a = \Delta E(0.5)$.[1] We can obtain a estimate of the lowest excitation energy of mercury by extrapolating our linear fit of data in Table I to $n = 0.5$.

We estimated the lowest excitation energy of mercury to be 4.76 ± 0.10 from the minima of the lock-in data estimated by eye, of the no lock-in data estimated by eye, and of the lock-in data estimated by curve-fitting.

V. DISCUSSION

Our main difficulty with this experiemnt was getting accurate values for the locations of the minima with small uncertainty. As you can see in Figures 4 and 5, there are gaps in the data, especially towards the higher values of accelerating voltage as the curve becomes steeper. When we zoomed in on each minimum to find the lowest point, the spacing between the points increased until it was difficult to tell where the minimum was. The scarcity and scatter in the points also made curve-fitting difficult, so that our various fits with igorPro

TABLE I. Values for minima spacing with uncertainty, determined by three methods: estimating by eye from the plot of lock-in data, estimating by eye from the plot of data taken without the lock-in, and calculating from the curve fits to the lock-in minima as described in the analysis section. Our eyeball estimates had the lowest uncertainty. The estimate by eye of the data without lock-in (columns 4 and 5 in the table) is plotted in Figure 6

	Lock-in data estimate by eye		Data without lock-in estimate by eye		Lock-in data calculated from fits	
n	X	dX	X	dX	X	dX
1	4.87	0.2	4.82	0.12	5	0.9
2	5.15	0.2	4.79	0.14	5.07	0.53
3	4.5	0.2	4.91	0.12	4.49	0.43
4	5.1	0.2	4.95	0.15	5.11	0.43
5	4.9	0.2	5	0.3	5.01	0.43
6	4.95	0.2	5.2	0.35	4.89	0.4
7	5.31	0.25	5.13	0.22	5.29	0.46

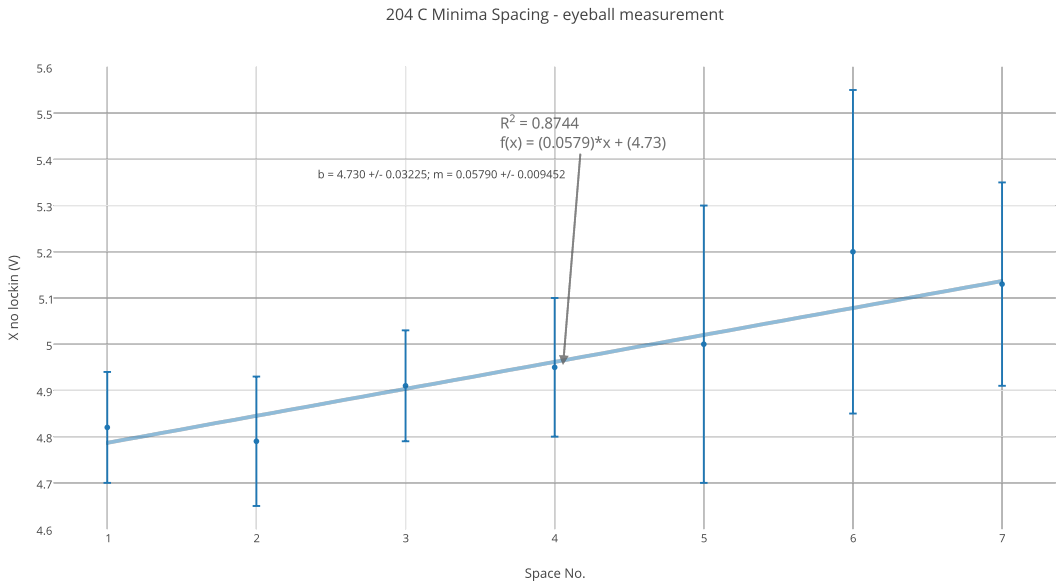

FIG. 6. A plot the change in accelerating voltage between successive minima.

and Mathematica had large error. Estimating by eye was equally difficult, and we could not

get the uncertainty below 0.12 V for any of our minima.

The solution to this ideally would be to take data with smaller increments of accelerating voltage, to fill in the gaps. However, we controlled accelerating voltage using a small knob on the control box, which did not allow for fine tuning. The scale on the readout went in steps of 0.5 V, and even turning the knob as slowly as we could, the accelerating voltage increased by steps of 0.2 V or greater, oftentimes slipping back to a smaller value before going up again. The large gaps in our data were caused by accidental twitches or bumps which, while feeling small, would cause the accelerating voltage to jump up. With the equipment we had, we took the most detailed data we could.

Of our two fits which we estimated by eye, only the data taken without the lock-in allowed for a decent curve fit. After calculating the first energy transition from this fit, we got a value which falls between the known transitions for mercury, and is in agreement with one. However, the uncertainty is too large to draw definite conclusions. The lowest two transition energies for mercury are 4.67 eV and 4.89 eV. Our value for the transition energy was: 4.76 ± 0.10eV, which is between these two transitions, and within uncertainty of the first transition energy.

VI. CONCLUSION

We saw dips in the output voltage, which was proportional to the electron current, as electrons were accelerated to higher and higher energies. The dips are caused by electrons losing energy to atoms through collisions, preventing them from reaching the cathode. We attempted to determine the minima location, thus spacing, using curve fitting techniques but the values we obtained contradicted our data upon inspection. Therefore, we estimated the minima location visually. The minima spacing increases linearly with the spacing number, and the lowest excitation energy can be determined from this. We found a value of for the 4.76 ± 0.10 eV lowest excitation energy of mercury. This does agree the reported value of 4.67 eV. We can improve the accuracy and precision our experiment in a few ways. One would be increasing the control for the accelerating voltage, so smaller increments could be made, increasing the number of data points. This would increase the definition of our minima and make it easier to determine their locations. Another would be finding a new way to compute minima locations more quickly and with more reasonable error using a data

analysis program.

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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).