Franck-Hertz Experiment Lab Report*

Xin Xiang†

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Abstract: The Franck-Hertz Experiment was the first electrical measurement to show the quantum nature of atoms. It was performed by James Franck and Gustav Hertz in 1914 using a vacuum tube with energetic electrons that flew through a vapor of mercury atoms. In this lab, we performed the Franck-Hertz Experiment using a mercury tube and a similar experiment using an argon tube. The quantized energy loss in electrons was observed in both experiments. The corresponding wavelengths of the spectral lines for mercury and argon during the Franck-Hertz procedure can be calculated by measuring the average energy loss during the collisions between electrons and atoms. We estimated the Plank constant with the wavelength of this spectral line that was given in advance. Although the spectral line corresponds to the 4.9eV due to the level transition of mercury atom cannot be directly seen because it is in the ultraviolet portion of the spectrum, we still conducted a spectroscopic analysis using a diffraction grating spectrometer to further investigate the atomic structure of mercury. The wavelengths of five mercury lines in the visible portion of the spectrum were measured and they agreed well will the theory.

I. INTRODUCTION

In 1914, James Franck and Gustav Ludwig Hertz, working at the Physical Institute of the Friedrich Wilhelm University of Berlin, published two papers describing their experiment on investigating the discharge of electrons that flew through mercury vapor atoms[1]. Their experiments were designed to investigate the nature of ionization of atoms by collision, the theory developed by John Sealy Edward Townsend. In their first paper[2], they discovered that only a specific amount of energy loss (4.9 eV) in the energetic electrons occurred during their collision with mercury atoms. This amount of energy loss was later confirmed, in their second paper [3], to be the ultraviolet mercury resonance line at 253.6 nanometers(nm). These experimental results were consistent with the Bohr model for atoms that had been proposed the previous year by Niels Bohr, which was unmentioned by Franck and Hertz at the time. Instead, they argued for the Thomson-like atom in which spectral lines were emitted by electrons oscillating within an extended positive charge [1]. And an electron can oscillate at a frequency corresponding to 253.6 nm in a mercury atom. To confirm this picture of a quantized Planck oscillator and present the connection with Plank's quantum theory, they reversed the procedure in their first paper by equated the 4.9 eV to hv using the frequency $v = c/253.6nm$ and found the Plank constant within an error of 1 percent [1].

Franck and Hertz's experiments had radically changed physicists' understanding of the behavior of slow electrons undergoing collisions with atoms and molecules. Townsend's assumption that electrons lose their energy in a collision at all energies was incorrect. Instead, they had augured that the nature of the collisions was more complex that, if the electrons have kinetic energy smaller than the ionization energy of atoms, the electron is in general reflected, at the same time however suffering a specific amount of energy loss if the electrons have enough energy. Later in 1915, Bohr suggested that Franck and Hertz might not have been seeing ionization at all; instead, collisions had raised atoms to an excited state, the decay of which emitted the ultraviolet resonance line in mercury. During years of debating, until the end of 1918, Franck and Hertz have finally agreed that the onset of inelastic collisions in mercury vapor at 4.9 volts represented an excitation, not ionization, which provided strong evidence for Bohr's theory whose key feature was that an electron inside an atom occupies one of the atom's "quantum energy levels" [4]. "For their discovery of the laws governing the impact of an electron upon an atom", Franck and Hertz were awarded the 1925 Nobel Prize in Physics [5]

In this Lab, we reproduced the classical Franck-Hertz experiment using a mercury tube and performed a spectroscopic analysis on mercury using a diffraction grating spectrometer. We also performed a Franck-Hertz-like experiment on argon. We will introduce the theory of the Franck-Hertz experiment and the diffraction grating spectrometer in section II. Then we will demonstrate our experiments' procedure and present the data analysis in sections III and IV.

II. THEORETICAL CONSIDERATIONS

A. Franck-Hertz Experiment in 1914

In their first paper published in April 1914, Franck and Hertz designed a new apparatus (see figure 1) that employed a cylindrical geometry consisting of a central filament D, a concentric accelerating platinum mesh at N, and a concentric collecting electrode G, to measure the ionization potential of mercury. The apparatus was immersed in an atmosphere of mercury vapor at a temperature around 120^oC with a vapor pressure of around one mm [6]. The electrons were emitted from the electrically heated cathode on D. A variable voltage between D and N was applied to accelerate to electrons. A con-

* PHYS 4321 - Advanced Lab

† Physics Department, Georgia Institute of Technology.

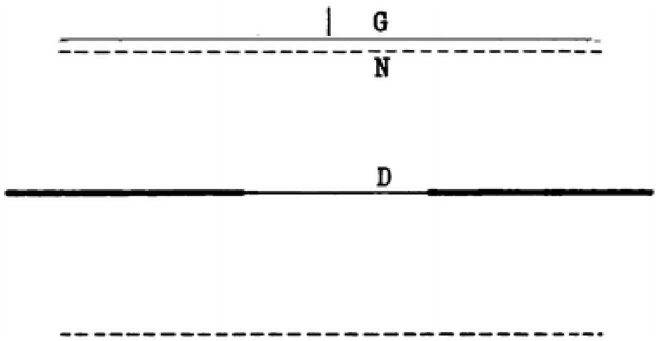

FIG. 1. Franck and Hertz's 1914 apparatus. This is a cylindrical geometry consisting of a central filament D, a concentric accelerating platinum mesh at N about 4 cm from D, and a concentric collecting electrode G, separated from N by "1 or 2 mm." Source: [2]

stant opposite voltage of about 0.5 volts between N and G was applied to decelerate the electrons and prevent low-energy electrons from being collected on G[1]. As the accelerating voltage between D and N increases, the current collected by G increased. This means that all the electrons flew through the mercury vapor without energy loss, thus the collision between electrons and mercury atoms in this phase is elastic. However, as the accelerating voltage reached around 4.9 eV, the current suddenly dropped to nearly zero, which meant that an electron lost nearly all its energy in a collision with a mercury atom between D and N. It could no longer overcome the opposing voltage between N and G and can not be collected by G. This energy loss of 4.9 eV from the electron was absorbed by the mercury atom during the inelastic collision. This amount of energy was later believed to be the minimum energy for mercury to be excited to the first state from the ground state (corresponds to the 254 nm transition line between state ${}^1S_0(6s^2)$ and ${}^3P_1(6s6p)$ in figure 2). As the accelerating voltage continued to increase, the current increase again until 9.8 eV, when electrons were able to loss all their energy in two collisions. Thus a series of maximums and minimums with interval of 4.9 eV were discovered (see figure 3). This implies that the gas molecules can only absorb energy from the electrons only at specific electron energies, called resonant energies. According to Planck's law, which was proposed in 1900 and soon became the fundamental law for quantum physics, the energy of radiation was given by:

$$E = h\nu = h\frac{c}{\lambda} \tag{1}$$

, where h is the Planck constant ($h = 6.626 \times 10^{-34} m^2 kg/s$), ν and λ are the frequency and wavelength of the spectral line, c is the speed of light ($c = 3 \times 10^8 m/s$). The energy E is equal to the energy loss of the electrons, which can be measured from the voltage difference between each adjacent minimum or maximum (ΔV) of the current-voltage curve. Given the lowest res-

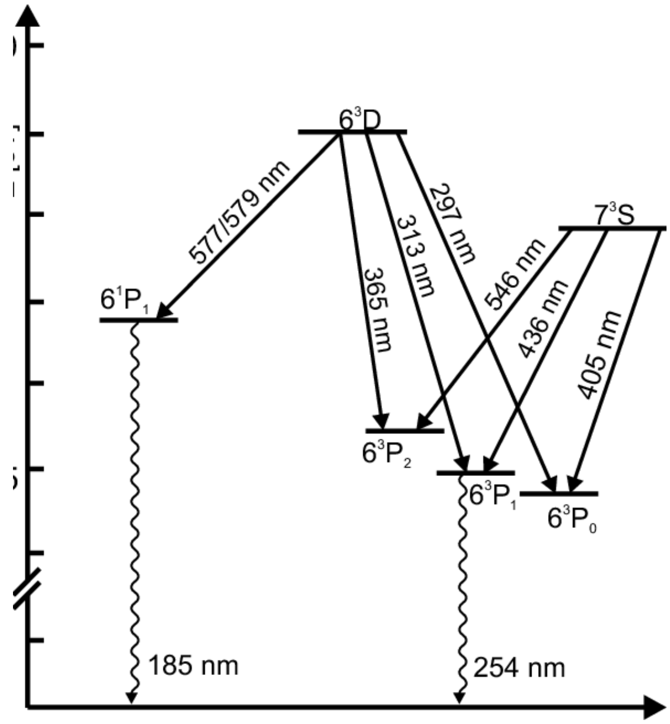

FIG. 2. Simplified Mercury Energy Level [7]

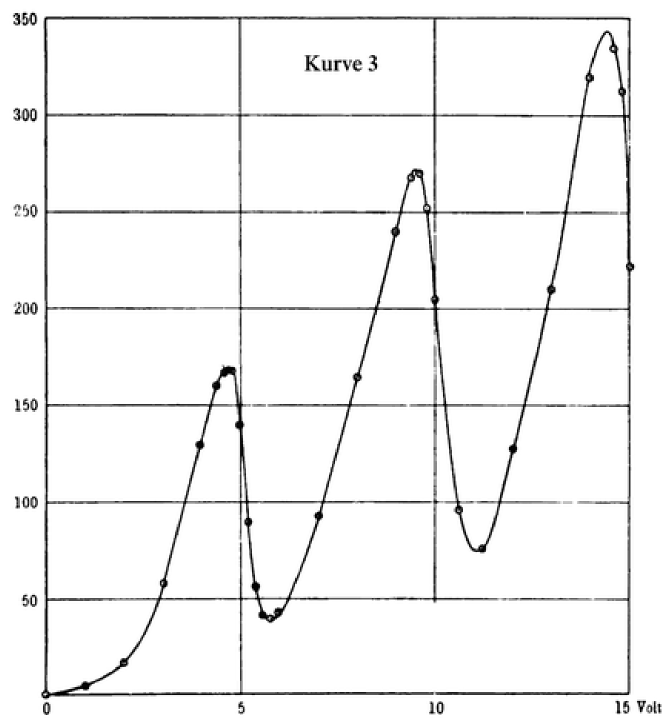

FIG. 3. Franck and Hertz's 1914 graph of current vs. accelerating voltage. This curve showed the interval of 4.9 eV. Source: [3]

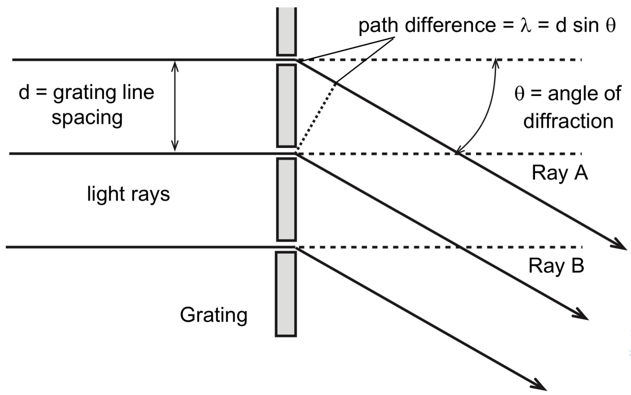

FIG. 4. Ray diagram for a singly wavelength. Source: [8]

onant energy for the gas molecule, we can estimate the Planck constant. The equation 1 can be rewritten as:

$$h = \Delta V \lambda / c \tag{2}$$

B. Diffraction Grating

The diffraction grating is a useful tool to separate the different spectral lines associated with the different atomic transitions for the incident light. It is a large number of parallel slits that are spaced equally by distance d. The incident light can be diffracted by the grating at all angles. Only a specific angle can form a light spot (a maximum) on the screen. Figure 4 shows the diffraction pattern for light rays with wavelength λ. The path difference between the adjacent diffraction rays needs to be exactly equal to the incident wavelength so that they can have constructive interference and make a maximum light spot on the screen. The constructive interference requires:

$$\lambda = d \sin\theta \tag{3}$$

The diffraction angle can also be zero and $-\theta$ to have constructive interference. All the other diffraction angles will be completely destructive. If the incident light is a combination of various different rays with different wavelengths, they can be separated by the grating because the constructive angles are different for different rays. Figure 5 illustrates the separation of the wavelengths of incident light. All the light sources are in phase at the middle peak (m = 0). The spectral image on the screen is symmetric about the middle peak. The different peaks in one side of the middle line represent light rays with a different wavelength from the incident light. The intensity for each peak is affected by the diffraction envelope, which is determined by the grating space (d). By measuring the angles for these peaks, we can determine the wavelength of different spectral lines for the incident light source.

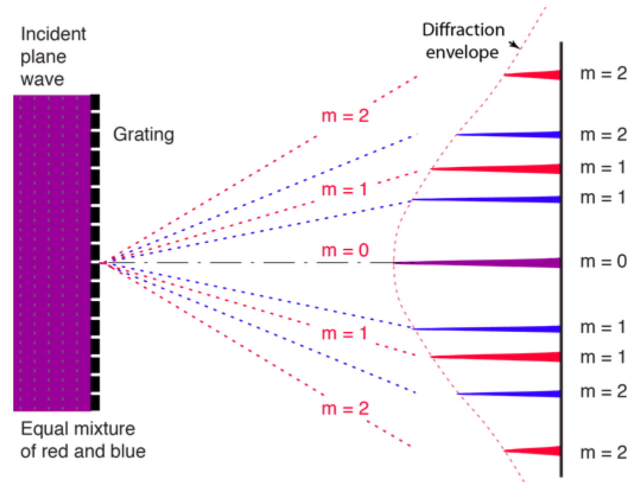

FIG. 5. The separation of the incident light by the grating. Source: [9]

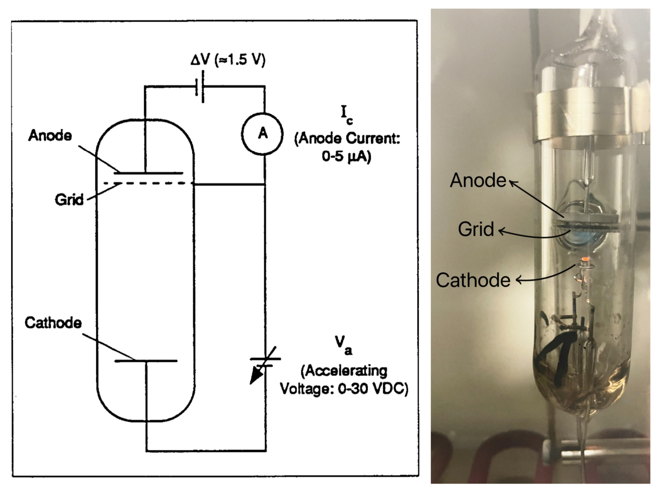

FIG. 6. Diagram of a mercury tube. The picture on the right is taken during the experiment. The Diagram on the left is from the Experiment Manual: [10]

III. EXPERIMENTAL METHODS

We performed two Franck-Hertz experiments to investigate the atomic process in mercury and argon atoms and one experiment using diffraction grating to further investigate the atomic structure of mercury.

A. Franck-Hertz experiment for mercury atoms

We used a vacuum tube containing mercury gas that was mounted in an heating oven. The figure 6 shows the design for the mercury tube. Similar to the origin apparatus used by Franck and Hertz, the electrons were emitted by the heated cathode that was connected to a power supply of $7.8eV$, and were accelerated by a po-

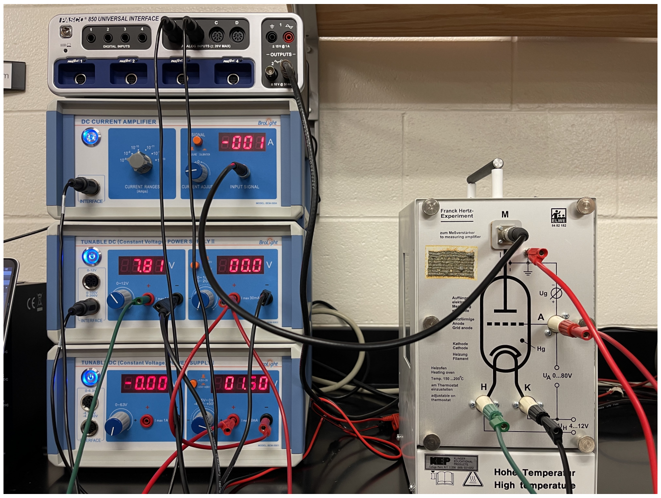

FIG. 7. Experiment setup for mercury tube

tential V_a between the Cathode and the Grid that could be varied from 0 to 30 eV. An opposing voltage of $1.5eV$ was applied between the Grid and the Anode. The Anode was connected to a sensitive current amplifier so that the current due to the electrons reaching the Anode could be measured. Figure 7 shows the connection of this mercury tube to the power supply. After the oven heated up the tube to approximately 200^oC, we slowly increased the accelerating potential to $45eV$ and recorded the Anode Current and Accelerating Voltage with the help of the PASCO Data Acquisition Software. Figure 9 shows the data collected for the four trials we performed. Figure 10 shows three images of the mercury tube during the experiment. The electrical breakdown occurred in Run3. Figure 11 shows how the breakdown looked like in the mercury tube.

B. Franck-Hertz experiment for argon atoms

We changed the apparatus to an argon tube shown in figure 8. The argon tube was heated by the Filament K that is connected to a power supply of $1.8eV$. The electrons were emitted from the grid G1, an indirectly heated oxide-coated cathode that was connected to a power supply of $V_{G1K} = 1.5eV$. The electrons were accelerated by a potential V_{G2K} between G1 and G2 that could be varied from 0 to 85 eV. The current amplifier was connected to Anode A which has a similar function as that for the mercury tube mentioned in the previous section. After 15 minutes of warm-up for the apparatus, we slowly increased the accelerating voltage to $85eV$ and recorded the data for the three different trails (See figure 12). The accelerating voltage for the first peak, the moment when the electrons have the exact amount of energy to excite the atoms, didn't match the peak difference because the contact potential was established between the two grids[12].

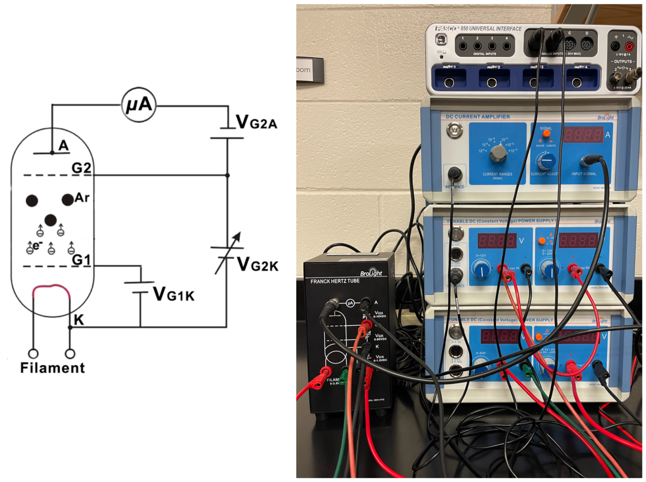

FIG. 8. Diagram and Setup for an argon tube. The picture on the right shows the connection of the tube box to the power supply. The picture on the left shows the design of the argon tube from the Experiment Manual: [11]

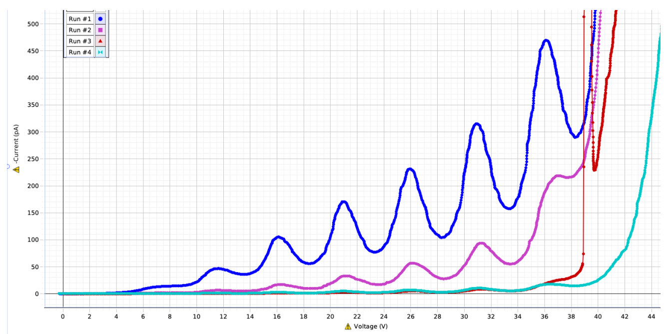

FIG. 9. The current-voltage curve for the three runs of Mercury Tube.

C. Diffraction Grating Spectrometer

To further investigate the atomic structure of mercury, we performed a measurement for the wavelengths of the colors in the spectrum of a mercury vapor light using a diffraction grating spectrometer with grating line spacing $d = 1666nm$. The light source of the mercury vapor light transmits through the Collimating slits and lens which change the large opening source into a narrow beam in the direction perpendicular to the diffraction grating (Figure 13 shows the experiment setup). The spectrum was scanned by the light sensor in the middle of the screen that was rotated slowly in one direction of the central ray. The data for light intensity and the angle were collected during the scanning process.

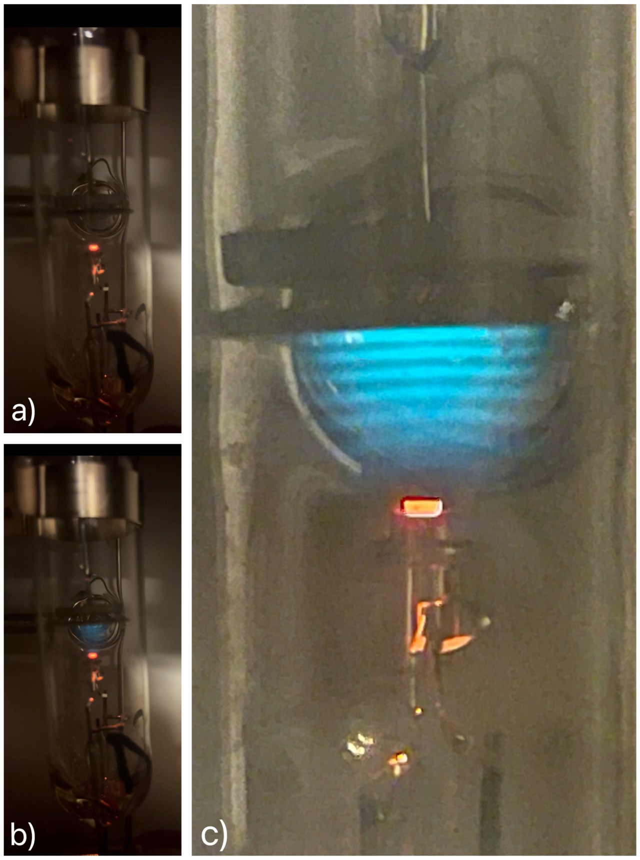

FIG. 10. The images of the mercury tube that was taken during one run. a) was taken after the temperature of the tube reached approximately 200^oC and the accelerating potential was 0. b) was taken when the accelerating potential was around 26 eV. c) was taken when the accelerating potential was around 80 eV.

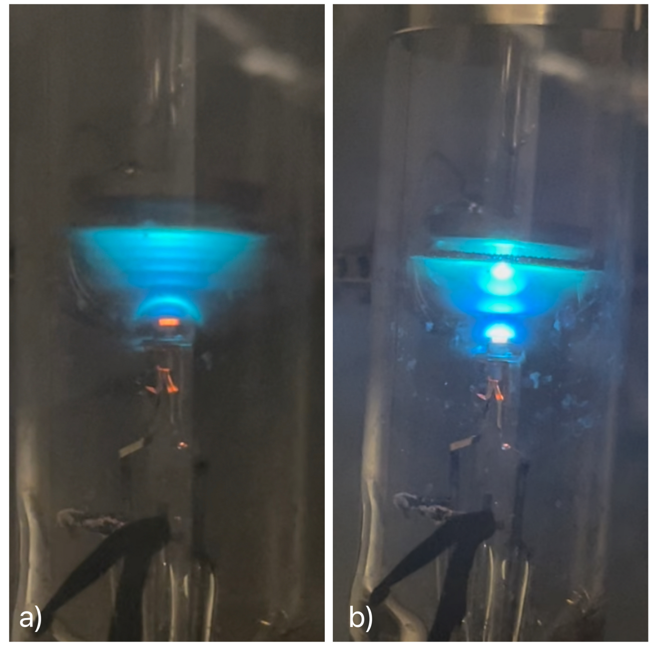

FIG. 11. The image for electrical breakdown of mercury atoms during run3

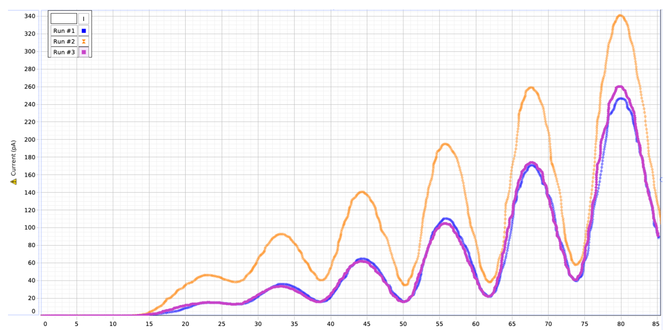

FIG. 12. The current-voltage curve for the three runs of Argon Tube.

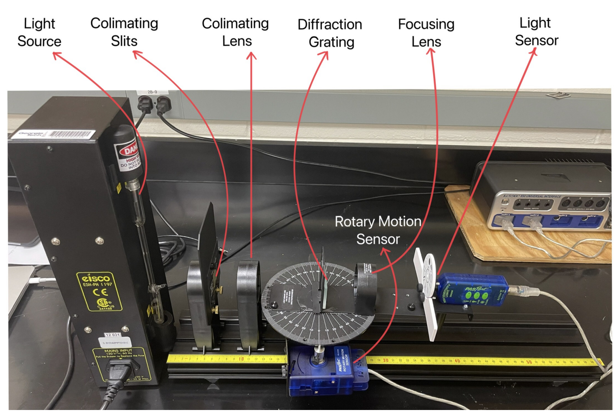

FIG. 13. The equipment Setup of a Grating Spectrometer

IV. DATA ANALYSIS

A. Franck-Hertz Experiment

We recorded the peak voltage values and through voltage values for each run in the current-voltage curve. The data are shown in figure 14 for the mercury tube and in figure 15 for the argon tube.

We used the numpy data analysis in python to calculate the linear regression line for the peak voltages and trough voltage. The uncertainties of the slopes were the standard deviations of the difference between adjacent peaks and trough.

The slopes of the regression lines are the energy loss of the electrons during each collision with the atoms. Taking the means value of the slope for the peak the through, we have $\Delta V_m = 4.99$ for the mercury atoms and $\Delta V_a = 11.53$ for argon atoms. The wavelength corresponding to the energy transition during the collision for the atoms is 254 nm (see the transition line in figure 2) for mercury atoms and 108.1 nm for argon atoms. Us-

FIG. 14. The data for the three runs of the mercury tube.

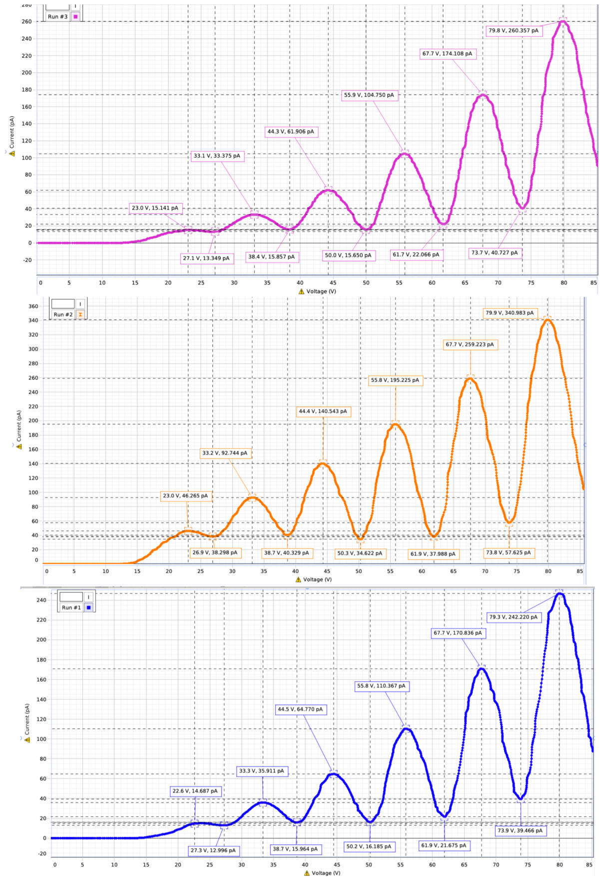

FIG. 15. The data for the three runs of the Argon tube.

ing the equation 2, we can estimate the Planck constant as $h = 6.758 \times 10^{-34}$ and $h = 6.658 \times 10^{-34}$, which are very close to the theoretical value (6.626×10^{-34}) with errors of 2% for the mercury experiment and only 0.48% for the argon tube.

B. Diffraction Grating Spectrometer

The central ray was at an angle of $\theta_0 = 0.622^o$. The measurement for the mercury spectrum is shown in figure 18. The diffraction angle for each wavelength is $\theta - \theta_0$. By using the equation 3, we can calculate the wavelength for each spectral line. The calculation result is shown in the table I

V. CONCLUSION

All the three experiments had good results that agreed well with the theory. One thing can be improved might be the apparatus for the mercury tube we used during the experiment. The estimation of the Planck constant using the data from the mercury tube has a much larger error than the argon tube. We noticed that for the run2 of the mercury tube, the last peak was so narrow that

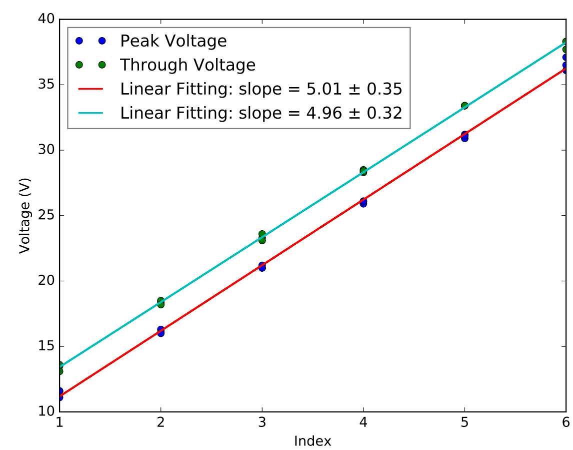

FIG. 16. The linear regression for the data of mercury tube.

the measurement may be deviated by a large number. If we eliminate the last peak data for the run2 of mercury tube, we got a more accurate result of $h = 6.703 * 10^-34$ with an error of 1.1%. But it is still not as good as the argon tube. The difference between the mercury tube and the argon tube was the heating methods and the tube box. The tube box for the mercury tube had a hole

TABLE I. Data table for the spectrum of mercury vapor lamp.

color	brightness	$\theta(^o)$	$\theta-\theta_0(^o)$	$\lambda = dsin(\theta-\theta_0)(nm)$	Literature Value [13]	error (%)
Violet	weak	13.401	12.779	368.76	365	1.03
Violet	bright	14.684	14.026	404.79	405	0.05
Blue	very bright	16.003	15.381	441.88	436	1.15
Green	very bright	20.103	19.481	555.61	546	1.72
Orange	bright	21.332	20.710	588.89	579	1.71

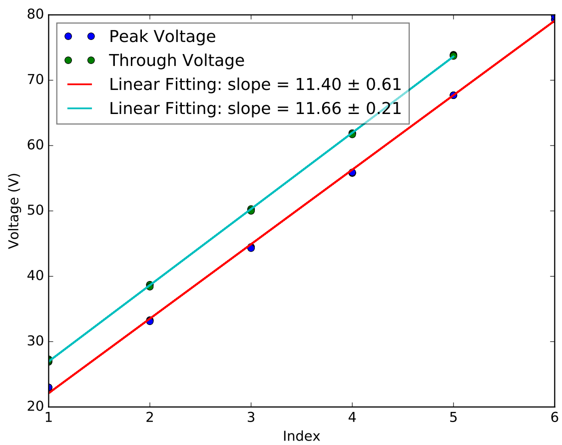

FIG. 17. The linear regression for the data of argon tube.

on top that was designed to have a thermometer, which was not provided for us. This hole on the top may be the reason for the larger error because the control of pressure and temperature inside the mercury box is not as good as the argon box. The narrow jump for the last peak of the mercury tube run2 may be due to the fluctuation of the temperature and the pressure inside the tube, which makes the measurement harder, thus, creates more error.

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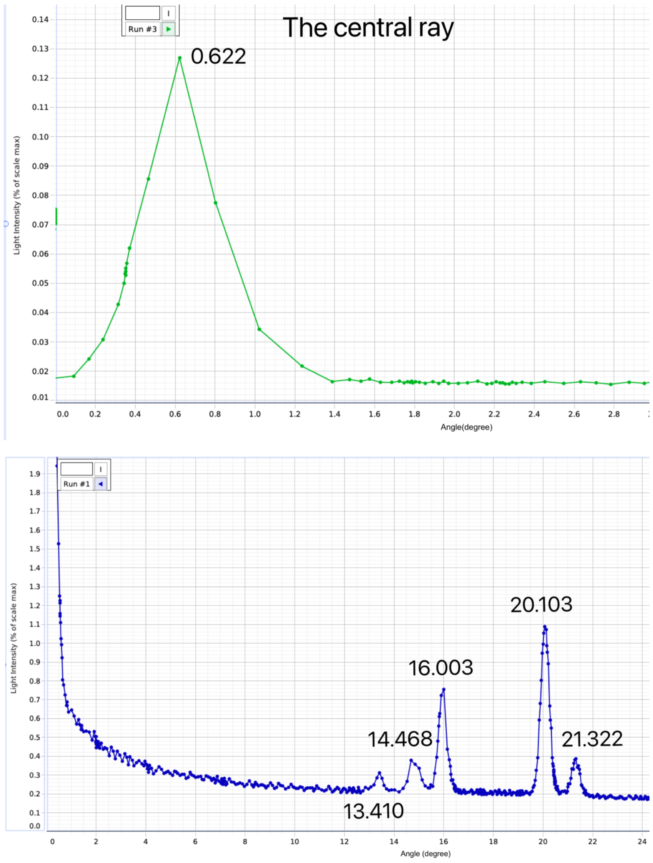

FIG. 18. The intensity vs angle data for the Diffraction Grating Spectrometer experiment.