

# Franck-Hertz and Photoelectric Effect

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## Introduction

The idea of quantized energies and discrete sets of quantum states is the backbone of quantum mechanics. The Franck-Hertz experiment and photoelectric effect are some of the most famous experiments to support this theory. We are able to show that electrons have specific energy levels and jump between these levels with the release and absorption of photons that have well defined energy levels according to their wavelength. Measuring this wavelength allows us to determine the energy lost or gained by the electron which tells us the magnitude of the new energy level.

In our study of the Franck-Hertz experiment, we will use the idea of discrete energy states to determine the wavelength of emitted radiation and prove the Stefan-Boltzmann Law.

In our study of the Photoelectric Effect and grating spectrometer, we will determine the work function of an anode,  $hc/e$ , and verify the emission spectrum of mercury and multiple light emitting diodes (LED).

## I. First Excitation Potential of Mercury

The apparatus we will use for this experiment uses more modern equipment than the original Frack-Hertz experiment but will function the same way. An evacuated glass tube contains a heated cathode, accelerating grid, and collector grid with mercury inside which will evaporate into

gaseous mercury once the tube heats up. Supplying the filament with a variable current allows us to control the temperature inside the tube and therefore the rate of electrons emitted by the cathode. The setup is shown in Figure 1.

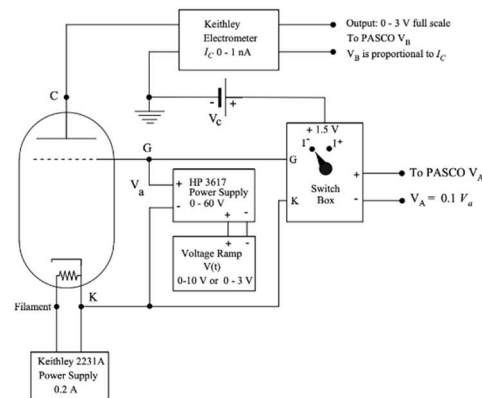


Figure 1: Franck-Hertz apparatus and circuit diagram

The collector current  $I_C$  and accelerating potential  $V_a$  are measured and plotted in Capstone for temperatures of 174.8°C, 185.8°C, and 195.3°C.

With the oven stabilized to within 0.2°C of the desired temperature, and the ramp voltage held at 55.5 V, the filament current is set to 185 mA and slowly increased until stable ~1 nA signal is received on the electrometer at 198 mA. The electrometer multiplier is switched from 3 back to 1 and ramp voltage adjusted to maximum. The ramp up is begun and the current  $I_C$  vs. voltage  $V_a$  is recorded, yielding the graphs shown in Figures 2, 4, and 6.

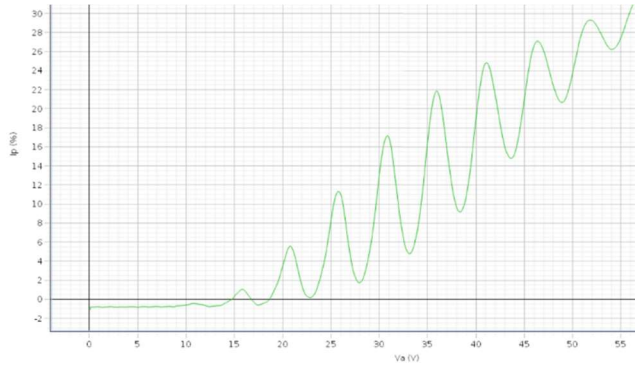


Figure 2: Franck-Hertz collector current  $I_c$  vs. accelerating potential  $V_a$  at 174.8°C

From this data we can calculate the excitation energy of the excited state  $\Delta V$  as the slope of  $V_a$  vs. peak number and contact potential  $V_{cp}$  as the intercept of the same fit. This is done for all three temperatures and the corresponding graphs can be seen in Figures 3, 5, and 7.

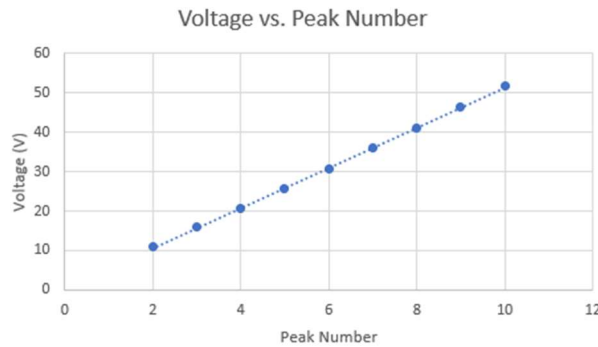


Figure 3: Franck-Hertz accelerating Voltage  $V_a$  vs. Peak Number for 174.8°C

$$\Delta V = 5.100 \pm 0.027 \text{ V}$$

$$V_{cp} = 0.42 \pm 0.18 \text{ V}$$

$$\lambda = \frac{hc}{\Delta V q} = 243.1 \pm 3.3 \text{ nm}$$

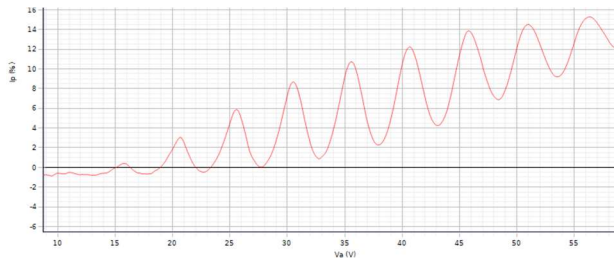


Figure 4: Franck-Hertz collector current  $I_c$  vs. accelerating potential  $V_a$  at 185.8°C

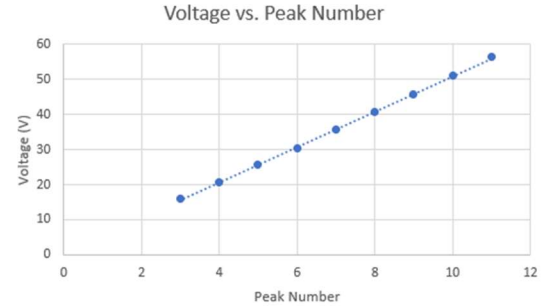


Figure 5: Franck-Hertz accelerating Voltage  $V_a$  vs. Peak Number for 185.8°C

$$\Delta V = 5.057 \pm 0.030 \text{ V}$$

$$V_{cp} = 0.40 \pm 0.22 \text{ V}$$

$$\lambda = \frac{hc}{\Delta V q} = 245.2 \pm 3.7 \text{ nm}$$

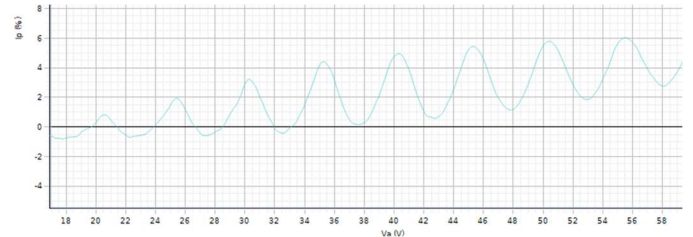


Figure 6: Franck-Hertz collector current  $I_c$  vs. accelerating potential  $V_a$  at 195.3°C

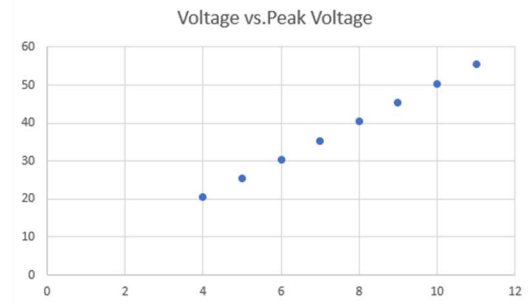


Figure 7: Franck-Hertz accelerating Voltage  $V_a$  vs. Peak Number for 195.3°C

$$\Delta V = 4.997 \pm 0.017 \text{ V}$$

$$V_{cp} = 0.42 \pm 0.14 \text{ V}$$

$$\lambda = \frac{hc}{\Delta V q} = 248.1 \pm 2.1 \text{ nm}$$

## II. Stefan-Boltzmann

The Stefan-Boltzmann law  $P = \sigma A T^4$  states that the radiation emitted from a

blackbody depends on its area and temperature. Using a tungsten filament in a lightbulb as our blackbody we can verify this law using the setup shown in Figure 8.

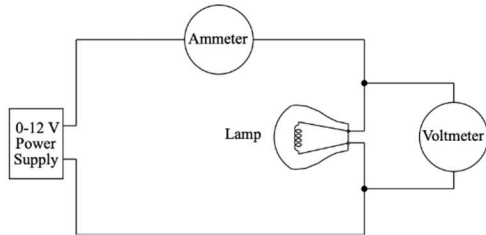


Figure 8: Tungsten filament circuit for Stefan-Boltzmann Law

The resistance of the filament can be used to measure the temperature of the filament because for tungsten the resistance and temperature are roughly linear. Measuring the resistance at room temperature we find  $R = 0.292 \pm 0.001 \, \Omega$ .

The current  $I$  was recorded as the supplied voltage  $V$  was varied from 1V to 10V in 1V increments. We can then determine the power  $P = VI$  and estimate the temperature with the polynomial expansion:

$$T \approx 103.4 + 215.2r - 3.03r^2 + 0.0447r^3$$

where  $r$  is the ratio of the resistance to the resistance at 300K.

We can then plot  $P$  vs.  $T^4$  which we expect as a straight line by the Stefan-Boltzmann law. The slope gives an estimate for the product  $e\sigma A$  where  $e$  is the emissivity,  $A$  is the surface area of filament, and  $\sigma$  is the Stefan-Boltzmann constant  $\sigma = 5.670 \times 10^{-8} \, \text{W/m}^2\text{K}$ . We are assuming that tungsten is an ideal black body where  $e \approx 1$ . This plot can be seen in Figure 9.

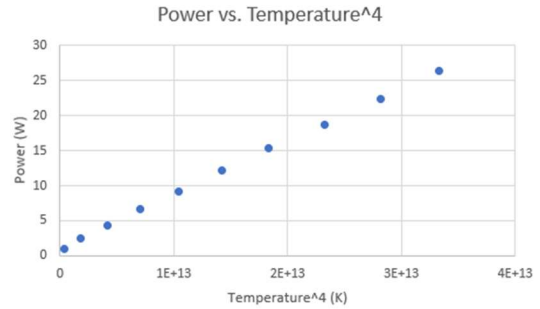


Figure 9: Power vs. Temperature<sup>4</sup> for tungsten filament

This slope yields a value of  $A = 13.49 \pm 0.11 \, \text{mm}^2$ . Measuring the filament size by sight it is estimated to be  $A \approx 1 \, \text{cm} \times 1 \, \text{mm} = 10 \, \text{mm}^2$ , which is relatively close to the calculated value.

### III. Photoelectric Effect

In this experiment we will explore the photoelectric effect from various spectral lines of mercury. The apparatus used is shown in Figure 10 with a filter placed between a mercury lamp and phototube. Four different interference filters are placed over the mercury lamp to isolate the yellow, green, blue, and UV spectral lines.

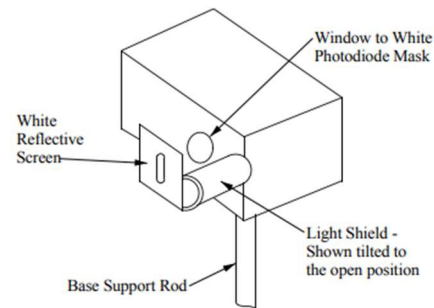


Figure 10: Phototube apparatus for measurement of the photoelectric effect

Multiple voltage measurements were taken for neutral, 20% and 100% intensity filters. This is done to prove that the output voltage depends only on the wavelength of light and material work function and not incident intensity. The graph for the output

voltage  $V_0$  vs  $1/\text{wavelength } 1/\lambda$  is shown in Figure 11.

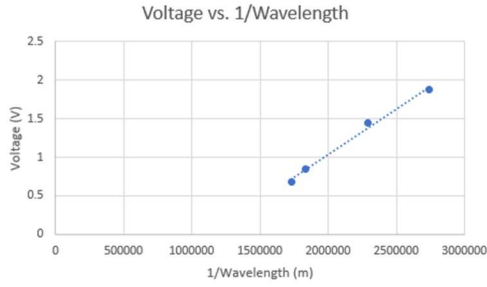


Figure 11: Voltage vs.  $1/\text{Wavelength}$  for photoelectric effect

$$V_0 = (hc/e) \times 1/\lambda - W_a / e$$

The value for  $hc/e$  can be found as the slope of this graph and  $W_a$  as the intercept.

$$hc/e = 1.188 \times 10^{-6} \pm 0.070 \times 10^{-6} \text{ V} \cdot \text{m}$$

$$W_a = 1.34 \pm 0.15 \text{ eV}$$

#### IV. $hc/e$ with LEDs

This experiment was performed in the dark to prevent ambient light from interfering with data acquisition. After our eyes had adjust to the darkness, we adjusted the current through a diode until we could see the light emitted from the LED just barely turn on, measuring the voltage across the diode each time. This was done separately for both experimenters to observe the biological bias in the procedure. We can find the value for  $hc/e$  by plotting the voltage threshold  $V_{th}$  vs.  $1/\lambda$  as shown in Figure 12 and 13.

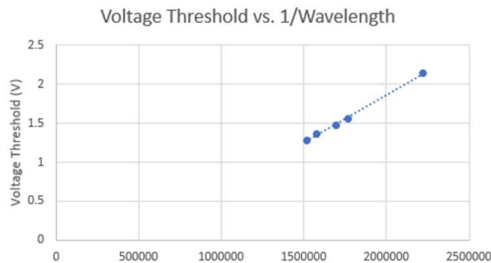


Figure 12: Voltage threshold vs.  $1/\text{Wavelength}$  for Duncan

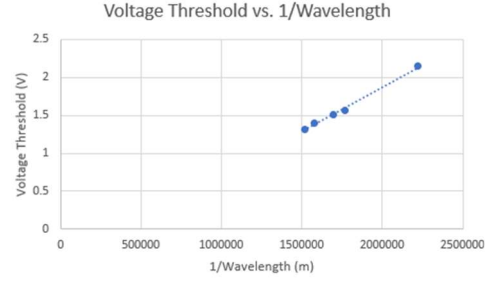


Figure 13: Voltage threshold vs.  $1/\text{Wavelength}$  for Charlotte

Using the relationship  $V_{th} = (hc/e) \times 1/\lambda$ , we know that the slope of these graphs will be our value for  $hc/e$ .

$$hc/e_D = 1.210 \times 10^{-6} \pm 0.043 \times 10^{-6} \text{ V} \cdot \text{m}$$

$$hc/e_C = 1.166 \times 10^{-6} \pm 0.045 \times 10^{-6} \text{ V} \cdot \text{m}$$

#### V. Grating Spectroscopy

In this experiment we will use a diffraction grating spectrometer setup as shown in Figure 14. This creates an image

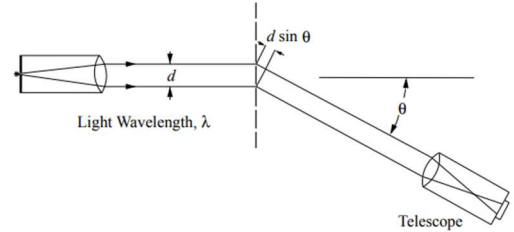


Figure 14: Diffraction grating spectrometer diagram

of the emission spectrum of the light source that is mirrored over the horizontal axis. Therefore, we can get a more accurate measurement of the diffraction angle  $\theta$  by finding half of the angle between a spectral line and its mirror image. The wavelength can be determined from the grating constant  $N = 600,000$  lines/m using the relation:

$$\lambda = \frac{1}{N} \sin \theta$$

Using a mercury lamp as the light source we can find values for each spectral line as shown in Table 1.

Table 1: Mercury Spectral Lines		
Color	Wavelength (nm)	Angle
Yellow (long)	584.0	20.51
Yellow (short)	581.8	20.46
Green	550.6	19.29
Blue	439.5	15.29
Violet	408.0	14.17

Using various LEDs as the light source we can find values for their spectral lines as well as shown in Table 2.

Table 2: LED Spectral Lines		
Color	Wavelength (nm)	Angle
Red	660.3	23.34
Orange	629.3	22.19
Yellow	585.3	20.56
Green	563.1	19.75
Blue	441.3	15.36

## Conclusion

In our first experiment with the Franck-Hertz apparatus we determined that the wavelength of the emitted photon was in the UV range of radiation and all three values were within three standard deviations of the accepted spectroscopic value of  $\lambda = 253.7$  nm. The largest possible source of error in this experiment is the rate of electron emission from the cathode as the tube temperature tended to vary by about  $\pm 0.2^\circ\text{C}$  during data acquisition.

In the second experiment with the Stefan-Boltzmann Law we proved, with the help of some precise approximations, that the Stefan-Boltzmann Law holds and can even be used to estimate the area of an object.

In our experiment with the photoelectric effect, we proved that the output voltage from the incident radiation

does not depend on the intensity of the radiation. We also showed that the value for  $hc/e$  can be determined from this technique as our experimental value is within one standard deviation from the theoretical value.

Similarly, we were able to determine  $hc/e$  by finding the voltage threshold of an LED. This, however, is a less accurate way to measure the constant because there is biological bias introduced as each observers' eyes also have an intensity threshold.

In our final experiment we used grating spectroscopy to measure the wavelength of specific visible light very accurately. These measured values are within one standard deviation from the predicted values. Grating spectroscopy is one of the best ways to record desired wavelengths as very fine adjustments can be made quite easily for more accurate results.