Photoelectric Effect Experiment

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***Abstract*—The experiment aims to calculate the ratio of the Planck Constant and the charge of the electron. The experiment is done by removing an electron from a surface with a light beam that has an energy $h\nu$, and stopping the electron by applying a voltage. According to the conservation of energy, the ratio is calculated. In this experiment we have found that the h/q ratio is $-2.249 \times 10^{-15} \pm 0.022 \times 10^{-15} V/Hz$. The recommended value is $-4.136 \times 10^{-15} C\,J\,Hz$.**

I. Theory

The Photoelectric Effect is a phenomenon observed when electromagnetic radiation hits a material, such as light [1]. In 1887, the effect is observed by Heinrich Hertz [2]. The theory of the Photoelectric Effect is proposed by Einstein in 1905 [3]. He proposed that the light is a tiny energy packet and the energy is proportional to its frequency. According to Einstein, a photon carries energy with $h\nu$, where h is the Planck Constant.

According to the Einstein's proposition, we have tested the following theory:

Energy of photon:

$$E_{photon} = h\nu \tag{1}$$

Kinetic Energy of Emitted Electron:

$$E_{kinetic} = \frac{1}{2}mv^2 \tag{2}$$

Maximum Energy Before Electrons are Emitted:

$$K_{\max} = h\,\nu - W, \tag{3}$$

where W is the minimum energy to remove an electron

Combining eq.2 and eq.3:

$$E_{kinetic} = K_{\max} \Rightarrow h\nu = W + \frac{1}{2}mv^2 \tag{4}$$

If a voltage is applied until the electron is stopped:

$$E_{kinetic} = qV_s \Rightarrow h\nu = W + qV_s \tag{5}$$

Manipulating the equation to obtain a linear equation:

$$\frac{h}{q}\nu = \frac{W}{q} + V_s \tag{6}$$

Here, we can see that there should be a linear relationship between $\frac{h}{q}$ and V_s. We assumed that there is a minimum energy requirement W, to remove an electron from the surface.

II. Method

Eq.6 suggests that the stopping potential and frequency of the light beam are proportional. From this suggestion, we have tested the phenomenon with different frequencies. We have used; yellow, green, turquoise, blue, and violet colors. There are different wavelengths associated with these colors, so they have different frequencies. For all colors, we tested the phenomenon with different voltages.

1) Light beam is produced with high pressure mercury lamp.
2) The produced light is refracted to different wavelengths with a prism.
3) The orientation of the grating is adjusted to obtain the desired color.
4) The refracted light is applied to remove electrons.
5) Voltage is increased to 3.000V, and observed a minus current. (This effect is due to the light falling to the anode part of the photocell [1])
6) Voltage is decreased and voltage-current data are taken.

III. The Experimental Setup

- High pressure mercury lamp with power supply. (Produces light)
- Spectrograph with a transmission grating. (Separates light to different wavelengths)
- Photocell with housing. (Emits electron)
- Current Amplifier. (Amplifies current to voltage)
- Moving Coil.
- DC Voltmeter. (One for voltage, one for current)
- Voltage Source.

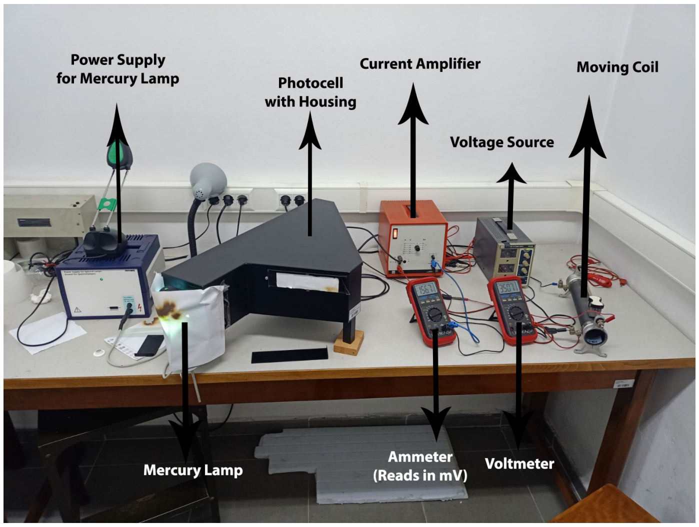

Fig. 1. Apparatus.

Fig. 2. Inside the housing. The mercury lamp is covered with a paper. The prism is at the top left part. Photocell is at the right bottom part.

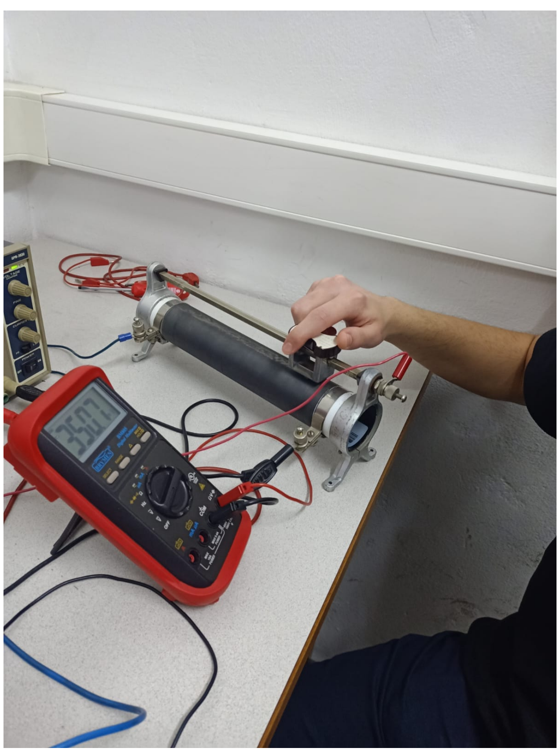

Fig. 3. Arranging moving coil to obtain different voltages.

IV. The Data

TABLE I
Volt and Current for Yellow

Volt(mV)	Current(fA)
3000. ± 1.	-112. ± 1.
2719. ± 1.	-100. ± 1.
2509. ± 1.	-95. ± 1.
2285. ± 1.	-85. ± 1.
2049. ± 1.	-82. ± 1.
244.7 ± 0.1	1. ± 1.
229.6 ± 0.1	12. ± 1.
34.8 ± 0.1	125. ± 1.
38.1 ± 0.1	121. ± 1.
76.0 ± 0.1	98. ± 1.

TABLE II
Volt and Current for Green

Volt(mV)	Current(fA)
2998. ± 1.	-128. ± 1.
2748. ± 1.	-121. ± 1.
2502 ± 1.	-116. ± 1.
2255 ± 1.	-112. ± 1.
2002 ± 1.	-105. ± 1.
350.6 ± 0.1	1. ± 1.
313.3 ± 0.1	13. ± 1.
18.0 ± 0.1	356. ± 1.
42.5 ± 0.1	312. ± 1.
72.7 ± 0.1	257. ± 1.

TABLE III
Volt and Current for Turquoise

Volt(mV)	Current(fA)
2998. ± 1.	-112. ± 1.
2753. ± 1.	-103. ± 1.
2502. ± 1.	-98. ± 1.
2251. ± 1.	-90. ± 1.
2001. ± 1.	-85. ± 1.
299.3 ± 0.1	-2. ± 1.
225.5 ± 0.1	25. ± 1.
16.3 ± 0.1	171. ± 1.
32.3 ± 0.1	153. ± 1.
77.1 ± 0.1	118. ± 1.

TABLE IV
Volt and Current for Blue

Volt(mV)	Current(fA)
3000. ± 1.	-113. ± 1.
2761. ± 1.	-108. ± 1.
2501. ± 1.	-100. ± 1.
2221. ± 1.	-93. ± 1.
1973. ± 1.	-87. ± 1.
312.4 ± 0.1	-13. ± 1.
206.6 ± 0.1	12. ± 1.
23.0 ± 0.1	79. ± 1.
37.8 ± 0.1	71. ± 1.
62.5 ± 0.1	59. ± 1.

TABLE V
VOLT AND CURRENT FOR VIOLET

Volt(mV)	Current(fA)
2998. ± 1.	-172. ± 1.
2736. ± 1.	-161. ± 1.
2550. ± 1.	-155. ± 1.
2261. ± 1.	-142. ± 1.
2020. ± 1.	-134. ± 1.
732.0 ± 0.1	-9. ± 1.
695.0 ± 0.1	29. ± 1.
22.7 ± 0.1	103. ± 1.
41.9 ± 0.1	982. ± 1.
66.9 ± 0.1	917. ± 1.

V. THE ANALYSIS

We have investigated volt and current values for different colors. So, there are 5 sets of data. As the eq.6 suggests, there should be a linear relationship between $\frac{h}{q}$ and V_s. To obtain V_s values of different colors, we have used the data. As can be seen from Fig.4-8, there are two different behaviors for the system.

The first behavior is due to the photoelectric effect, which we want to experiment according to the eq.5. After the needed V_s value is reached, we see a negative current which is the leakage current. The second behavior is nearly a constant horizontal line. To achieve a reasonable V_s value, we have calculated the intersection of these two lines. The x-axis of the intersection is V_s. To calculate the uncertainty of V_s, the uncertainty propagation is done according to the formulas:

Slope of the Line-1: m_1

Slope of the Line-2: m_2

Intercept of Line-1: n_1

Intercept of Line-2: n_2

$$V_s = (n2 - n1)/(m1 - m2) \tag{7}$$

$$f = aA \ \Rightarrow \sigma_f = |a|\sigma_A \tag{8}$$

$$f = \frac{A}{B} \ \Rightarrow \sigma_f \approx |f|\sqrt{\left(\frac{\sigma_A}{A}\right)^2 + \left(\frac{\sigma_B}{B}\right)^2 - 2\frac{\sigma_{AB}}{AB}}[4] \tag{9}$$

If A and B values are independent, $\sigma_{AB} = 0$.

$$f = \frac{A}{B} \ \Rightarrow \sigma_f \approx |f|\sqrt{\left(\frac{\sigma_A}{A}\right)^2 + \left(\frac{\sigma_B}{B}\right)^2} \tag{10}$$

where, f is the function

A and B are corresponding variables

σ_A and σ_B are corresponding uncertainties

a and b are corresponding constants.

The line fit is done by Root's built-in function. (See Appendix).

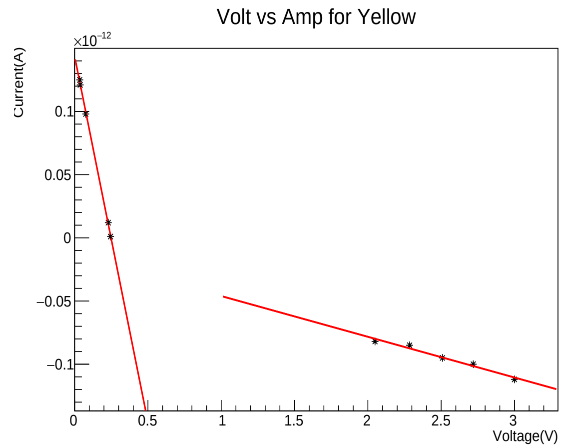

Fig. 4. Interception of Lines: 0.288 +- 0.007 V

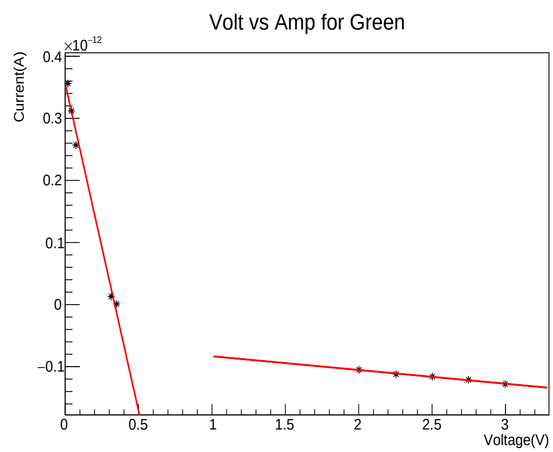

Fig. 5. Interception of Lines: 0.404 +- 0.003 V

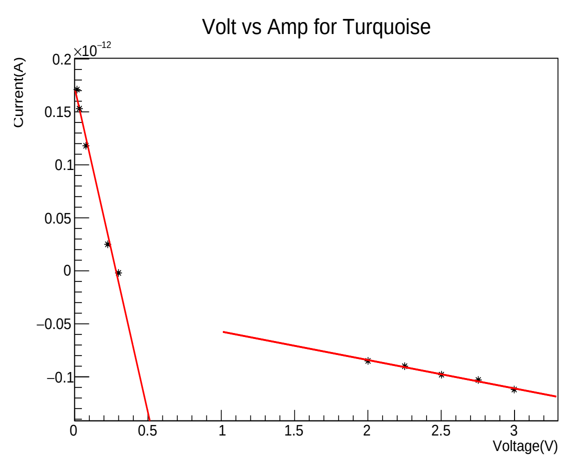

Fig. 6. Interception of Lines: 0.347 +- 0.006 V

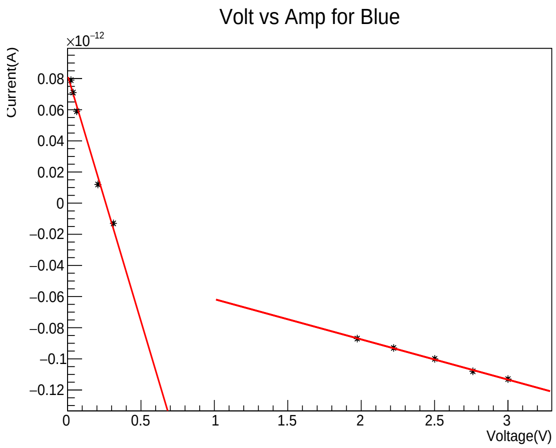

Fig. 7. Interception of Lines: 0.407 +- 0.012 V

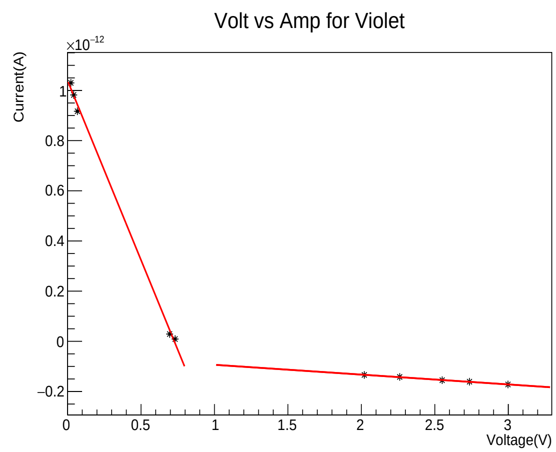

Fig. 8. Interception of Lines: 0.786 +- 0.003 V

We have collected V_s data with its uncertainty for corresponding frequencies. To find $\frac{h}{q}$ ratio, we have fitted these values to a straight line(See Fig.9).

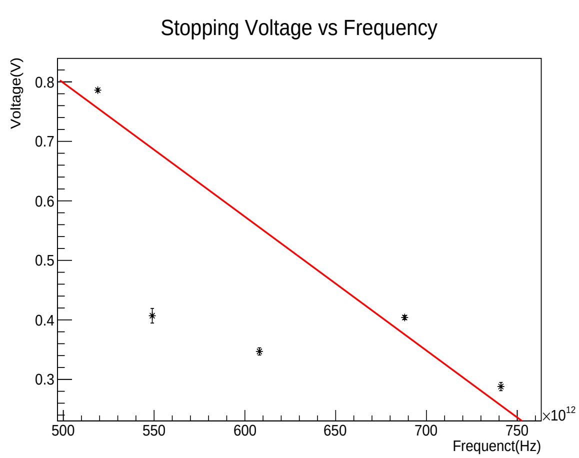

Fig. 9. Slope of the Line: -2.249e-15 +- 0.022e-15 V/Hz
y-Intercept of the Line: 1.923 +- 0.013 V

VI. The Result

We have found the h/q ratio to be -2.249×10^{-15} V/Hz with an uncertainty of 0.022×10^{-15} V/Hz. The CODATA recommended values for q and h are $q = -1.602\times10^{-19}C$ and $h = 6.626 \times 10^{-34}\ J\,Hz^{-1}$[5] [6] . So the recommended value for h/q ratio is $-4.136\times10^{-15}\ C\ J\ Hz$. There is a $\%45.62$ relative error, and the result we have obtained is 85,7 σ away from the recommended value.

VII. The Conclusion

The result we have obtained is far away from the recommended value. Therefore, we have concluded that the experiment was a failure. Even if we have tried to obtain the best data we can get, it is obvious that there were some issues. One of the issues is that the assumption we have made to obtain the eq.4. The material we have worked on is not near 0 Kelvin, so there is a thermionic emission. [7]

Another issue is that the environment we conducted the experiment is not adequate for this experiment. One observation we made is that when the desk lamp is turned on to read the data, the current value changed significantly. The effect may due to the electromagnetic interactions in the system. Since we had to read too small(fA) current values, any noise in the environment changes the reading.

The experiment could be conducted with fewer internal and external impurities. The magnetic and electric field around the apparatus could be eliminated by shielding the environment. The system could be cooled down to near 0 Kelvin for better results.

References

[1] E. Gülmez. *Advanced Physics Experiments*. 1st. Boğaziçi University Publications, 1999.

[2] *Ueber einen Einfluss des ultravioletten Lichtes auf die electrische Entladung*. URL: https://zenodo.org/record/1423827#.ZBhtK9JBxkg (visited on 03/19/2023).

[3] *"Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt"*. URL: http://myweb.rz.uni-augsburg.de/~eckern/adp/history/einstein-papers/1905_17_132-148.pdf (visited on 03/19/2023).

[4] *Strategies for Variance Estimation*. URL: https://www.sagepub.com/sites/default/files/upm-binaries/6427_Chapter_4__Lee_(Analyzing)_I_PDF_6.pdf%20html (visited on 03/12/2023).

[5] *CODATA Value: elementary charge*. URL: https://physics.nist.gov/cgi-bin/cuu/Value?e (visited on 03/19/2023).

[6] *CODATA Value: Planck constant*. URL: https://physics.nist.gov/cgi-bin/cuu/Value?h (visited on 03/19/2023).

[7] *"THERMIONIC ELECTRON EMISSION PROPERTIES OF NITROGEN-INCORPORATED POLYCRYSTALLINE DIAMOND FILMS "*. URL: https://web.archive.org/web/20161123053917/http://etd.library.vanderbilt.edu/available/etd-03262013-131559/unrestricted/Paxton_Thesis.pdf (visited on 03/19/2023).

VIII. Appendix

The fit has been done with Root's built-in function (See Fig4-9). We have used root release 6.28/00 for Ubuntu22.

Fitting for different colors:

```
{
 TTree *t = new TTree("t", "t");
 string color = "violet";
 t->ReadFile("violet.csv");
 float a,v;
 t->SetBranchAddress("A", &a);
 t->SetBranchAddress("V", &v);

 float * x, * y, * sx, * sy ;
 int n = t->GetEntries();
 x = new float[n];
 y = new float[n];
 sx = new float[n];
 sy = new float[n];

 float del_x = 0.1 * pow(10,-3);
 float del_y = 0.1 * pow(10,-14);

 float freqs[5] = {5.19, 5.49, 6.08, 6.88,
     7.41}; // yellow, green, turq, blue,
     violet
 float freq = freqs[4] * pow(10,14);

 for (int i = 0; t->LoadTree(i) >= 0; i++){
  t->GetEntry(i);
  x[i] = v * pow(10,-3);
  y[i] = a * pow(10,-14);
 }

 for (int i=0; i<n; ++i){
  sx[i] = del_x;
  sy[i] = del_y;
 }

 TGraphErrors *graph = new
     TGraphErrors(n,x,y,sx,sy);
 graph->Draw("A*");
 graph->SetTitle("Volt vs Amp for Violet");
 graph->GetXaxis()->SetTitle("Voltage(V)");
 graph->GetYaxis()->SetTitle("Current(A)");

 TF1 *line1 = new TF1("line", "[0] + [1]*x",
     0, 0.8);
 line1->SetParameters(0,0);
 graph->Fit(line1,"R");

 TF1 *line2 = new TF1("line", "[0] + [1]*x",
     1, 100);
 line2->SetParameters(0,0);
 graph->Fit(line2,"R+");

 float m1 = line1->GetParameter(1);
 float m1_error = line1->GetParError(1);
 float n1 = line1->GetParameter(0);
 float n1_error = line1->GetParError(0);
 float m2 = line2->GetParameter(1);
 float m2_error = line2->GetParError(1);
 float n2 = line2->GetParameter(0);
 float n2_error = line2->GetParError(0);

 line2->Draw("same");
 //Error Propagation for the slope
 float up = n2-n1;
 float down = m1-m2;
 float up_error = sqrt(n2_error*n2_error +
     n1_error*n1_error);
 float down_error = sqrt(m1_error*m1_error +
     m2_error*m2_error);
 float x_intercept = (n2 - n1) / (m1 - m2);
 float error = x_intercept *
     sqrt((up_error/up)*(up_error/up)+(down_error/down)*
 cout << "Stopping Voltage For " << color <<
     " = " << x_intercept << "+-" << error <<
     endl;
}
```

Fitting for h/q value:

```
{
 const int ndata = 5;
 double y[ndata] = { 0.786, 0.407, 0.347,
     0.404, 0.288};
 double x[ndata] = {5.19, 5.49, 6.08, 6.88,
     7.41};
 double sy[ndata] = {0.0026358, 0.0122895,
     0.00611123, 0.0034491, 0.00693817};
 double sx[ndata] = {0,0,0,0,0};

 double lambda_error = 10.0 * pow(10,-9);
 double light = 3.0*pow(10,8);

 for (int i = 0; i<ndata; i++){ // Error
     Propogation for Frequency
 double lambda = light/x[i];
 x[i] *= pow(10,14);
 sx[i] = x[i] * (lambda_error/lambda); //
     Error of Speed of Light = 0

 }
 double xmin = 300*pow(10,12);
 TGraphErrors *mygraph = new
     TGraphErrors(ndata,x,y,sx,sy);
 mygraph->Draw("A*");

 TF1 *fnew = new
     TF1("fnew","[0]*x+[1]",0,1*pow(10,15));
 fnew->SetParameters(0,0.5); // arbitrary
     starting parameters


 mygraph->Fit("fnew","M");

 mygraph->SetTitle("Stopping Voltage vs
     Frequency");
 mygraph->GetYaxis()->SetTitle("Voltage(V)");
 mygraph->GetXaxis()->SetTitle("Frequenct(Hz)");
 double slope = fnew->GetParameter(0);
 double y_int = fnew->GetParameter(1);
 double s_error = fnew->GetParError(0);
 double y_error = fnew->GetParError(1);
 cout << "h/q Ratio = "<< slope << " +- " <<
     s_error << endl;
 cout << "Intercept of the Line = " << y_int
     << " +- " << y_error << endl;
}
```