Author: G. Everton, wadh7166, December 2024

GP04: The Behaviour and Properties of an electron

Abstract: This lab was divided into 3 distinct parts. In part A we determined the mass / charge ratio of the electron by observing its motion in a uniform magnetic field and determined this value to be 7.0±0.5 kg C^{-1}. In part B we observed the wave-like nature of an electron by observing the diffraction pattern of an electron beam passing through a thin layer of graphite, and from our observations calculated a carbon – carbon bond length 0.145±0.002nm. Part C of the lab involved experimenting with a two Frank-Hertz tubes and using out measurements to determine the excitation energies of Mercury and Neon, which were found to be around 5 and 20 eV, although issues with our apparatus limited the accuracy of our results.

Introduction: For a particle of charge e moving with velocity $\boldsymbol{v}$ in a magnetic field $\boldsymbol{B}$ and electric field $\boldsymbol{E}$, the Lorentz force experienced by the particle is given by the equation $\boldsymbol{F} = e(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$ In our apparatus, $\boldsymbol{B} \gg \boldsymbol{E}$ and $\boldsymbol{v}$ is perpendicular to $\boldsymbol{B}$ and are of constant magnitude, so our equation simplifies to $F = Bqv$. Combining this with the equation for circular motion, $F = \frac{mv^2}{r}$, we obtain $R = \frac{mv}{eB}$. By considering the energy of the electron accelerated between the cathode and the anode, we obtain $\frac{1}{2}mv^2 = eV$, which rearranges to equation 2 $v^2 = \frac{2ev}{m}$(1). Combining these equations, we find that $\frac{e}{m} = \frac{2V}{(\mathrm{B}R)^2}$, where $B = \frac{m_0 NI}{a\left(\frac{5}{4}\right)^{\frac{3}{2}}}$. [1]

Hence if we plot I^2 against V we obtain a graph with a gradient of $\frac{2a^2\left(\frac{5}{4}\right)^3}{(m_0 NR)^2} \cdot \frac{m}{e}$ (2), which allows the value of $\frac{m}{e}$ to be calculated.

The second section of the experiment involved investigating the wave-like nature of a beam of electrons by observing the diffraction patterns of an electron beam as it passed through a thin layer of graphite. Since the de Broglie wavelength of these electrons is comparable to the distance between the carbon atoms, the beam diffracts.

We know that the wavelength of the electrons is given by $\lambda = \frac{h}{p}$, and since $p = mv$ and $E = \frac{1}{2}\,mv^2$, we obtain that $p = \sqrt{2mE}$, where E is the energy of the electrons, and can be calculated using $E = eV$ where e is the charge of an electron and V is the accelerating potential.

The Bragg Law states that $2d\sin\theta = n\lambda$. Taking $n = 1$ and combining this with our above equations, we find that $2d\sin\theta = \frac{h}{\sqrt{2meV}}$. Additionally, given the geometry of the apparatus we find that $D_r \approx 4L\theta$. By applying the small angle approximation and substituting in, we come to our final equation.

$D_r = \frac{2Lh}{d\sqrt{2me}} \cdot \frac{1}{\sqrt{V}}$ (3), where D_r is the diameter of a given diffraction pattern.

The third part of the lab involved the use of a Frank-Hertz tube. In this experiment electrons are given off from a heater element through thermionic emission and accelerated across a potential between two metal grids. The electrons then pass the electrode A and are decelerated to and collected at electrode S. The current flowing from electrode S is measured using an ammeter to give an indication of how many electrons reach this electrode. Since the inside of the tube is filled with a low-pressure gas (either Neon or Mercury), the electrons collide with these gas particles, and if they have sufficient energy, excite the atom, hence the electron loses a discrete amount of energy. By tuning the accelerating and braking potential, we can selectively measure the number of electrons with a given energy, and from this data calculate the discrete energy transitions occurring in the gas.

Mass Charge Ratio Method:

The aim of this part of the lab is to determine the mass / charge ratio of an electron. We do this by using the apparatus shown in Figure 1 [1].

The low-pressure Neon atmosphere inside the globe allows the electrons to travel mostly uninhibited, but also produces a dim glow along the path of the electrons due to photoelectric emission from Neon atoms excited in collisions with electrons.

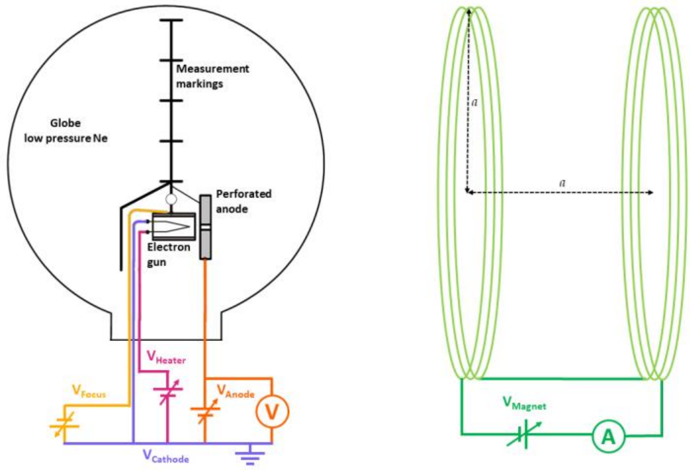

Figure 1

The varying anode voltage allows the speed of the electrons produced by the electron gun to be controlled and is related by equation (1). To obtain the results, the heater element was supplied with 6.5V and given 3 minutes to heat up before results were taken. Then the anode was raised to 300V and the focus adjusted, so that the faint beam seen in the globe was sharp.

The supply across the Helmholtz coils was then switched on and adjusted such that the beam passed through the second measurement marking in the globe. This was done by eye, taking care to avoid parallax errors when aligning the beam with measurement markings. This means the beam has a radius of 2±0.2cm, however the error in this was large due to the difficulty in seeing the beam. The current required to maintain this radii circle was recorded, then the anode voltage decreased by 20V and the measurements repeated, obtaining 6 data points on the range 200 – 300V. Then using equation (2) and the values given in the lab script [1], we can plot our results and use the gradient to determine $\frac{m}{e}$

Mass Charge Ratio Results:

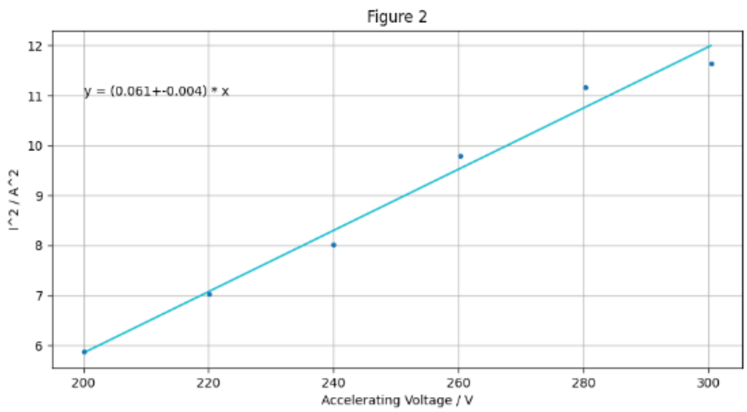

Figure 2 shows that the gradient of our line of best fit is $6.1 \pm 0.4 \times 10^{-2}$A²V⁻¹. Using Equation 4 and the following values:

$m_0 = 1.26 \times 10^{-6}$Hm⁻¹ $N = 124, a = 0.147$m, we obtain that $\frac{m}{e} = 7.1 \pm 0.5 \times 10^{-12}$kg C⁻¹.

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Electron Diffraction Method:

The main piece of equipment used in this experiment was an evacuated glass sphere containing an electron gun in one of the gun, a layer of graphite material suspended in the path of the beam to act as the diffraction grating and a phosphor coating on the other side of the sphere. When the electrons collide with this coating, a green light is emitted, allowing the diffraction patterns of the electrons to be observed. To take the measurements required, the heater supply was powered on and given a minute to warm up, then the EHT supply was powered on and varied from 2.5kV to 5.5kV in 0.3kV increments. At each accelerating Voltage the diameter of each circle observed on the glass was measure with a ruler. This measurement was hard to take by hand and was a major source of uncertainty in the lab.

Electron Diffraction Results:

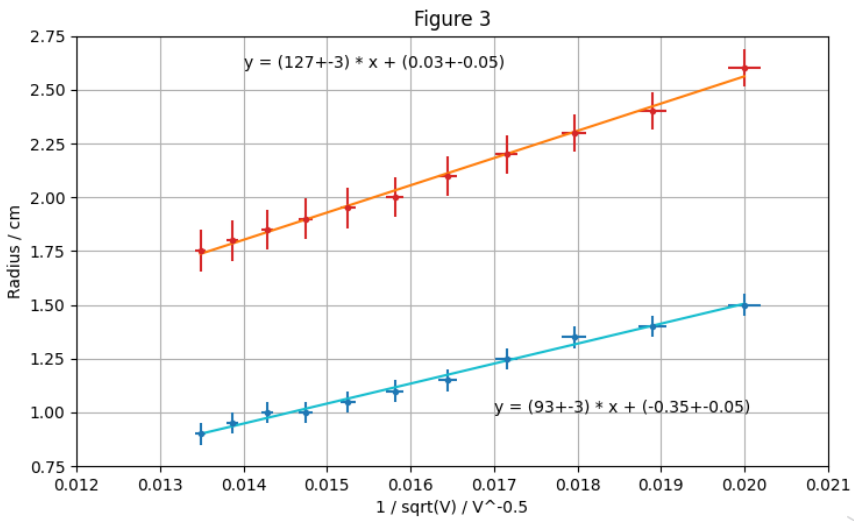

Figure 3 shows data obtained from the experiment. 2 circles were observed on the phosphor screen, and these two lines correspond to different distances between planes of atoms in the graphite.

Graphite is made of several layers of carbon atom arranged in a hexagonal lattice, as shown in Figure 4 [1], stacked on top of each other in random orientations. This results in several different planes of carbon atoms that the electrons can diffract from, as can be seen to the right. From the equation (3) derived earlier,

$$R_r = \frac{Lh}{d\sqrt{2me}} \cdot \frac{1}{\sqrt{V}}$$

we can plot our results and use the gradients to calculate d.

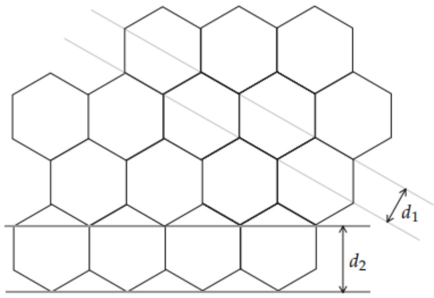

Figure 4

Taking $L = 13.5 \pm 0.1$, we find that $d_1 = 0.130 \pm 0.004$nm and $d_2 = 0.178 \pm 0.007$nm. Taking the average carbon – carbon bond length d_{C-C} to be 1.42×10^{-10}m, we find theoretical values of $d_{1Predicted} = d_{C-C} \times \cos 30 = 0.123$nm and $d_{2Predicted} = d_{C-C} \times (1 + \cos 30) = 0.213$nm

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Method & Results for Neon Tube:

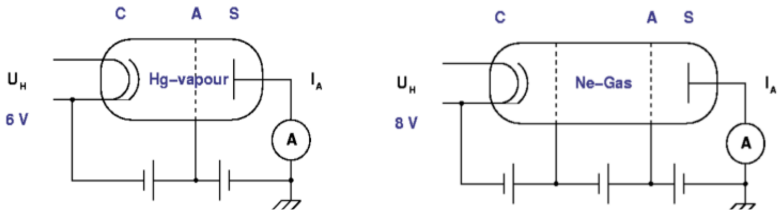

Figure 5

Figure 5 shows a schematic diagram of the apparatus used, with an extra accelerating potential U_3 being shown in the Neon experiment. First experimenting with the settings on the Neon tube, with $U_3 = 1.7\text{V}$, $U_2 = 0\text{V}$ and sweeping U_1 from 0 to 90V we observe an increasing number of emission bands of an orange colour consistent with a discharge of ~2.0eV, as shown in the sketch in Figure 6. Measuring the collector current from the ammeter at electrode S with a braking potential of 6.8V we observe the following graph. This sketch in Figure 7 shows a drop in the collector current at around 20V of accelerating potential, consistent with when the first orange band appears. This is a result of the electrons having an energy great enough to excite the Neon atoms and hence collide inelastically with them, transferring energy to the Neon atom, leaving the electron with insufficient kinetic energy to overcome the braking potential, and hence not causing current at the collector electrode. The peaks of this graph were analysed and the results shown below. This first peak to is consistent with the energy required for the electron configuration of Neon to transition from 2p^6 to 2p^{5}3s with an energy of 16.65eV [2]. The orange colour seen corresponds to the 2p^{5}3p → 2p^{5}3s transition of 18.7eV to 16.6eV.

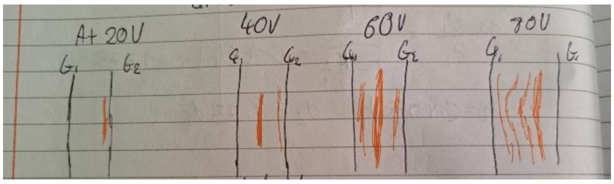

Figure 6

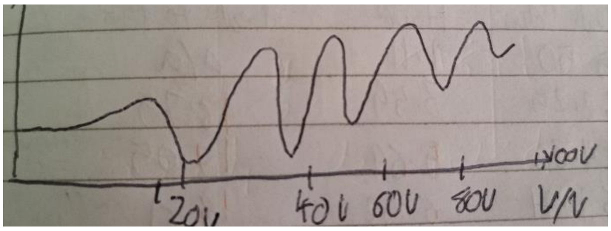

Figure 7

Peak	Voltage/V	Current / nA	Peak to Peak Voltage/V
0	15.50	1.11	n/a
1	32.25	3.59	16.75
2	49.30	5.69	17.05
3	67.91	6.52	18.61
4	88.03	6.80	20.12

Method & Results for Mercury Tube:

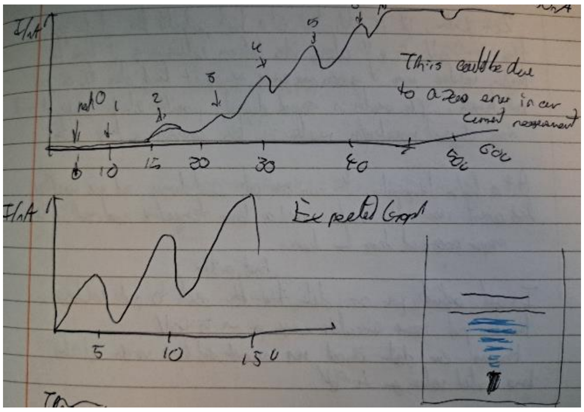

Figure 8

For the Mercury tube, we connected the apparatus and heated the oven to 175°C and set the heater potential $U_H = 4.8\text{V}$ and $U_2 = 0.8\text{V}$. It was difficult to get a smooth curve out of the apparatus with no current being recorded for accelerating potentials less than 15V. However, several peaks above 15V were observed. In Figure 8, the first sketch shows the data obtained, and the second shows the expected results. Additionally, at high accelerating potentials a blue discharge, like the one sketched was observed.

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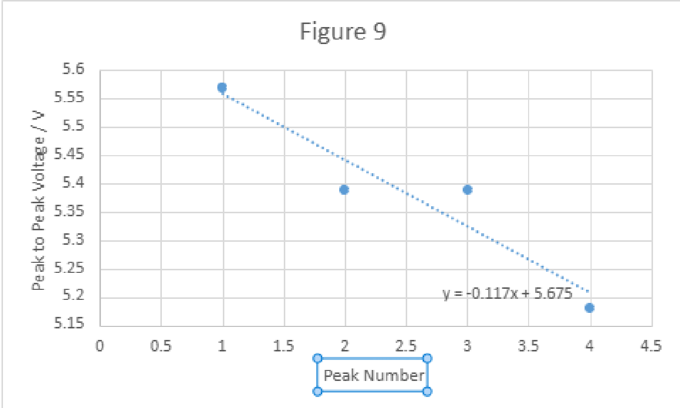
The peak-to-peak data is shown in Figure 9 and shows a peak-to-peak voltage of around 5.4V, which is close to the value of the $6^1S_0 \rightarrow 6^3P_1$ transition of 5.47eV [3]. The blue discharge observed is most likely a combination of the $7^1S_0 \rightarrow 6^3P_1$ transition and the $7^3S_1 \rightarrow 6^3P_1$ transition, as both release a wavelength of light of around 405nm, which would correspond to the blue colour observed.



Interpretation & Summary: The value we obtained for the mass / charge ratio of an electron was $7.1 \pm 0.5 \times 10^{-12}$kg C^{-1}, whereas the real value is $\frac{9.11\times10^{-31}}{1.6\times10^{-19}} = 5.69 \times 10^{-12}$kg C^{-1}[4][5], so a 25% error. The error in my measured value is most likely due to the difficulty in aligning the beam of electrons such that it was a fixed radius, as it is difficult to see and hence introduces a lot of error as the radius of the circle is not constant.

In the electron diffraction experiment the values we obtained were $d_1 = 0.130 \pm 0.004$nm and $d_2 = 0.178 \pm 0.007$nm. We also found predicted values of $d_{1Predicted} = 0.123$nm and $d_{2Predicted} = 0.213$nm. These values give us an error 6% in d_1 and 16% in d_2 Once again the source of these errors is the measurement of the diameter of the circles seen on the phosphor screen and could probably improve by photographing the apparatus with a reference scale and then measuring the distances digitally.

Finally, for the Frank-Hertz tubes, the results of the original experiment in validating Niels Bohr's model of the atom, as it proves that electrons in an atom can only occupy discrete quantised energy levels, demonstrated by the fact that an electron collides elastically with the Mercury atoms if it does not have enough energy to excite the Mercury atom to a higher energy level. Our execution of this experiment was not very successful as we did not observe the smooth expected graph at the low acceleration voltages, but we did find a voltage accurately representing the $6^1S_0 \rightarrow 6^3P_1$ transition, and observed the light being emitted in bands due to photoelectric emission from the excited Neon atoms in the experiment with the Neon tube.

References:

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