Proving the Proven

Testing Bohr's atomic theory and finding Neon's excitation energy in the Franck – Hertz experiment

Lab 1

Department of Physics, University of Toronto Scarborough PHYC11: Intermediate Physics Laboratory II

Professor Dan Weaver

11. Feb. 2024

Table of content

Authors

Ivan Pakhomov
Student number: 1008040013

Abstract

People have always been curious about the fundamental components and structure of the world. One of the most important theories that has emerged from this curiosity is Bohr's energy quantization theory, which sheds light on the structure of atoms. This paper presents experimental evidence for the theory, based on the Franck-Hertz experiment with neon gas. By studying the structure of neon atoms and comparing them to the results obtained from the experiment, it was possible to prove the theory. Additionally, it was discovered that neon has a metastable state and the energy of the first excited state was found.

Introduction

§ 1: Atomic models through history

Since ancient times, philosophers have been wondering about the nature and structure of our world. Different generations advanced the previous theories and created their own. Each time, the models seemed to fit the understanding of the world, and the physical laws developed until new concepts that were true but did not fit in the model were created. So, the physics had to be rethought and rebuilt each time to satisfy the observations.

The atomic model theory is one of the brightest examples of such a process. The ancient Greeks developed the first physical and mathematical laws of nature. They developed geometry, algebra, astronomy and the fundamental laws of mechanics. Some of these concepts remain unchanged to the present day. They were at the peak of technological development and were left to wonder about the structure of nature. They observed that anything can be broken into tiny pieces, and those pieces can also be broken down. At this point, the question that is still bothering scientists all over the globe arose: What is the fundamental 'unbreakable' unit in the universe? Around 450 BC, Democritus seemed to come up with an answer and came up with the proposition that all matter is made of invisible tiny particles - 'atomos' (in ancient Greek means 'uncuttable') (Pullman, 1998, pp. 31-33). This proposition became of the most important in the history of physics. For the next two thousand years, people have been trying to explain and explore the concept of atoms and their nature.

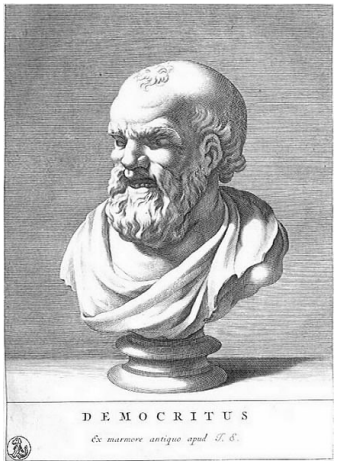


Figure 1. Democritus (Greek Philosopher)

The first atomic theory that could explain the theory present at that time was introduced by the English school teacher John Dalton (1766 -1844). The main points of his theory are (Dalton, J., & Thomson, T. 1970):

1. All elements are made of tiny particles - 'atoms.'
2. Atoms of identical elements are identical, while atoms of different elements are different.
3. Atoms can neither be destroyed nor created.
4. Atoms of different elements combine to form chemical elements in constant ratios.

These propositions came from his study of gases and various chemical elements. However, his theory was not immediately accepted by the scientific community.

In the late 19th century, J.J Thomson (1856 - 1940) discovered that all atoms contain electrons - negatively charged particles that weighed almost 1800 times less than the hydrogen atom. This discovery made Thomson suggest that the neutral atom consisted of negatively charged electrons distributed in a uniform positive charge (Pullman, 1998, p. 384). This theory seemed perfect until, in 1909, Ernest Rutherford (1879 - 1937) discovered that most of the mass was concentrated in the center of atoms. He discovered this due to the phenomenon of scattering of the alpha particles passing through the gold foil (Pestka, J. 2017). Based on this observation, he proposed the 'planetary model,' unlike Thomson's plum pudding model; he stated that most of the mass and a positive charge of the atoms are concentrated in the center of the atom, and electrons orbit it (just like planets orbit the Sun).

Figure 2. Niels Bohr

However, this theory could not exist in classical physics for two reasons. The first reason is that an accelerated charged particle emits electromagnetic waves in classical electromagnetism. In Rutherford's model, electrons orbit the nucleus, meaning they have a constant centripetal acceleration and thus need to emit radiation and lose energy. However, if electrons were to give off energy constantly, they would collide with the nucleus. Secondly, this model cannot explain the discrete emission spectrum of the hot gases (Scherrer, R. J. 2005).

The solution came with the development of quantum mechanics, and in 1913, Niels Bohr (1885 - 1962) proposed his model of atoms where electrons orbit the nucleus with quantized energy levels.

§ 2: Bohr model and Franck–Hertz experiment

In his paper (Bohr, N. 1913), Bohr describes the Hydrogen atom and proposes that electrons have quantized energies:

$$W = \tau h \frac{\omega}{2} \tag{1.}$$

where W is the amount of energy transferred to the system to remove the electron, the entire number, h - Planck's constant, and ω - frequency of revolution. (Bohr, N. 1913 pp. 3-5)
This is a fundamental relation that we still use today. In the derivation of the energy levels for the Hydrogen atom, he also assumed that:

1. That the dynamical equilibrium of the systems in the stationary states can be discussed by help of the ordinary mechanics, while the passing of the systems between different stationary states cannot be treated on that basis.
2. That the latter process is followed by the emission of a homogeneous radiation, for which the relation between the frequency and the amount of energy emitted is the one given by Planck's theory.

The first assumption tells us that we cannot describe the behaviour of the electron between different stationary states by ordinary mechanics. The second assumption tells us that the process of the electron going from a higher energy state to a lower energy state is followed by the emission of radiation, with energy being the difference in the atom's energy levels.
Using these assumptions and formula (1.), he derived that the frequency of the emitted radiation in a Hydrogen atom is:

$$\nu = \frac{2\pi^2 m e^4}{h^3}\left(\frac{1}{\tau_f{}^2} - \frac{1}{\tau_i{}^2}\right) \tag{2.}$$

Where τ_i and τ_f are initial and final energy levels respectively.
Unfortunately, even Bohr's model was bound not to be complete since eq.(2.) could not give a correct estimation for atoms containing more than one electron. However, his energy quantization ended up being a successful and useful theory, as was shown by many experiments, including the Franck–Hertz experiment.

Figure 4. Gustav Hertz

Figure 3. James Franck

James Franck (1882 –1964) and Gustav Hertz (1887–1975) are German physicists who won the Nobel Prize for Physics in 1925 'for the discovery of the laws governing the impact of an electron upon an atom.' Their paper '*Über Zusantmenstöfse zwischen Elektronen und den Molekülen des Quecksilberdampfes und die Ionisierungsspannung desselben*' (German for 'On collisions between electrons and molecules of mercury vapour and the ionization voltage.') described their experiment performed with the mercury vapour on the elastic and inelastic collisions with slow electrons. They discovered that only electrons having certain energies could inelastically collide with the mercury vapour (they found that electrons need to have 4.9 eV of energy in order to inelastically collide with Hg vapour.) (Franck 1926). With this experiment, they proved that Bohr's theory of quantum energy level was indeed correct. This was a major breakthrough and gave birth to new theories and models.

In the experiment, we wish to recreate the Franck–Hertz experiment with neon atoms and put Bohr's model to the test. We also want to analyze the atomic structure of the neon atoms. In addition, we are interested in the effects of the initial conditions on the obtained data and various fluctuations that may appear.

Method

§ 1: Apparatus

The experiment was conducted using the evacuated glass tube filled with the monoatomic gas at room temperature to a gas pressure 10 hPa (in our case, neon was used). The glass tube contained a system of four electrodes (see Figure 5).
The way this apparatus works is straightforward: cathode (a.) is being warmed up, and, as a result, free electrons accumulate on its surface. Under the influence of the constant driving potential U_1, the electrons are emitted towards the grid (b.) and form a charge cloud. After passing (b.), electrons are accelerated by the electric field $E_2 = U_2/d$ until they reach grid (c.). In the region between (b.) and (c.), electrons collide with atoms of the neon gas and, upon reaching grid (c.), have a particular value of kinetic energy. If the energy of the electrons entering the region (c.) to (d.) is greater than eU_3 (energy given to the electron by U_3), then the nonzero current is detected. However, if the energy value is smaller, electrons do not reach the electrode and get stuck on the control electrode (c.) and, as a result, no current is detected.

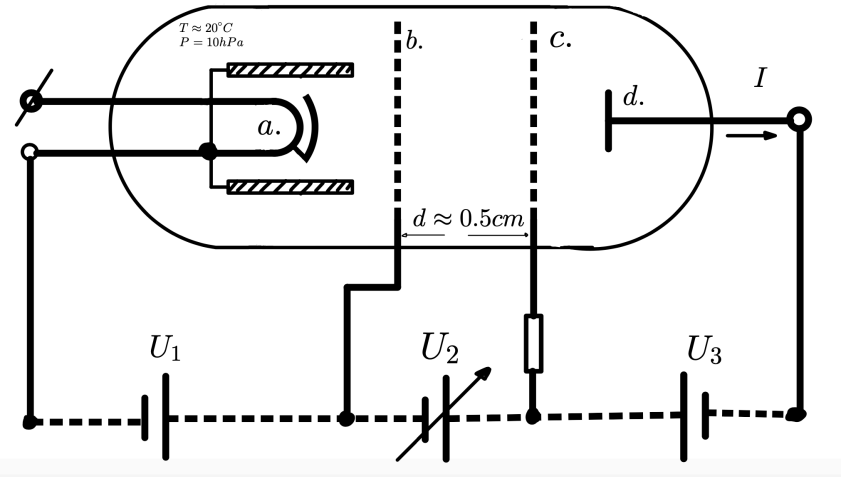


Figure 5. Schematic representation of the apparatus used.
a.) electrons-emitting cathode; b., c.) grid-shaped controle electrode; d.) collector electrode; U_1 – constant driving potential between a.) and b.); U_2 – variable acceleration potential between b.) and c.); U_3 – constant braking potential between c.) and d.).

§ 2: What happens between the control grids?

As electrons are accelerated through the region b.c., they gain energy $\epsilon = eE_2z$ (I chose ϵ to denote the energy to avoid confusion with the electric field E) where e – charge of the electron, E_2 – magnitude of the electric field corresponding to the potential U_2 and z – distance from the grid b.) (so $z = d$ at grid c). As per Bohr's theory (refer to the introduction, § 2), it is expected to observe a decrease in current at specific values U_2 since when the energy of free electrons is sufficient enough to excite the electrons in the gas atoms, they will collide inelastically and transfer all their energy to the gas. This results in a lack of energy for the free electrons to overcome the braking potential.

§ 3: Gas used in the experiment

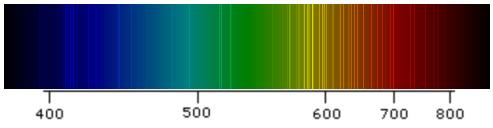


Figure 6. Spectral lines of neon in visible range, with the wavelength measure in (nm)

The experiment can only be performed using the inert gases or the metal vapours. The reason is that atoms in such gases have zero electronegativity and, thus, do not form anions (negative ions) when the free electrons are attached. The latter stay rather as free ones, even if they are moving slowly inside a dense gas (Franck 1926). This is a vital factor for the success of the experiment since, if not for this property, the electrons would form negative ions with the atoms, and no current would be detected.
In our case, the inert gas neon was chosen. Neon is a noble gas with the atomic number 10 and the electron configuration $1s^2 2s^2 2p^6$. In Figure 7, we may see neon's energy levels, where $1s_0$ corresponds to the ground level and in Figure 6, the spectral lines are shown.

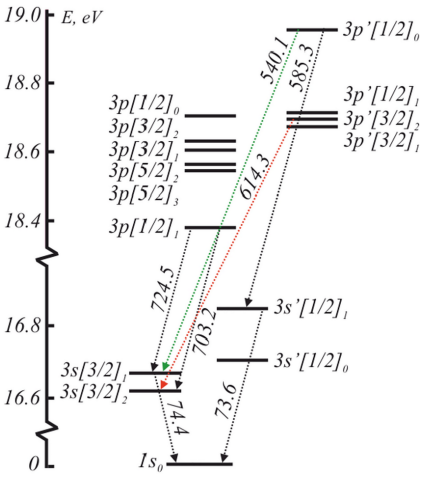


Figure 7. Neon's energy levels and emitted radiation wavelengths in nm

Results

§ 1: Experiment setup

In order to establish the relation between the excitation energy of the neon atoms and the energy of the free electrons, we studied the relation between the detected current and the accelerating potential under various initial conditions (initial conditions being the values of U_1 and U_3). Two sets of experiments were conducted to obtain the most accurate data. First, the driving potential was kept constant at a value of 5 V, while the braking potential was changed for every measurement. Secondly, the braking potential was kept constant at 5 V, while the driving potential was varied.
In addition, the emission light was captured for various settings of U_1, U_2 and U_3.
The following sections describe the results obtained.

§ 2: Driving potential – variable, Braking potential 5.00 V

This section is devoted to the data obtained when we set $U_3 = 5.0V$ and let U_1 vary.
Figure 8 contains various curves. Different colours represent different initial conditions.
In general, we see that the behaviour of the curves is identical. The only difference between them is that all the values of the current detected are higher for higher driving potential. It is worth mentioning that the three lowest curves do not carry sufficient information because their behaviour can only partially be determined.
We see that for a small accelerating potential, the detected current for all curves is 0 (The initial peaks at 0 come from the apparatus being turned off and on after the measurements started, so it is not physically meaningful and can be neglected).
When the accelerating potential is around 3.5 V, all curves start rising rapidly, and at approximately 5 V, their growth rate decreases. Once the maximum value is reached, the curves decrease until they get a minimum (the values of local maximums are in Table 1). Now, the curves start growing again. It is necessary to mention that the growth rate after the first minima is smaller than the initial growth (see Discussion for the reasons). When the current reaches the second minimum, we see a sudden minor increase (this increase corresponds to the 3rd peak in Table 1), which vanishes quickly. The curves start growing again at approximately the same rate as towards the second maxima. Once the curves reach the third maxima, they do not go down, as could be expected; they instead fluctuate around a stable value, and for a relatively high potential, we see an increase (again at the same rate as before) and no further decrease until the end.

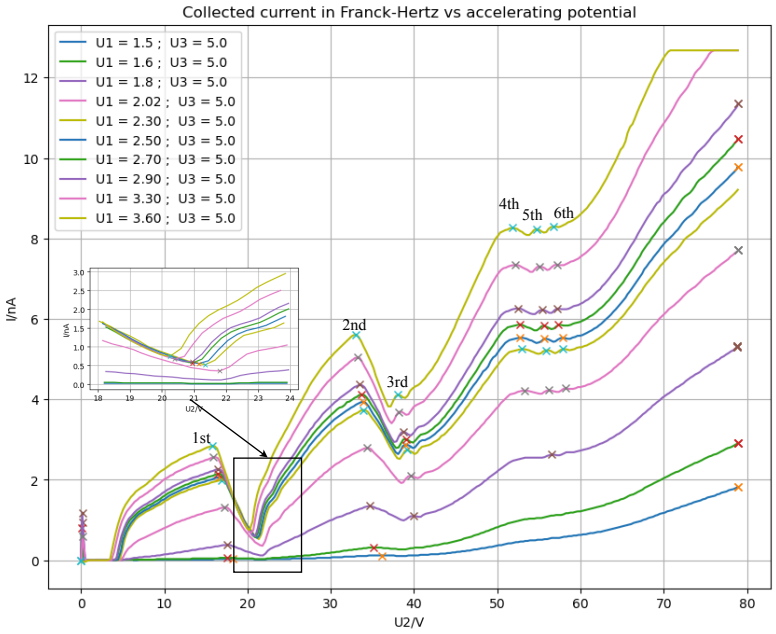


Figure 8. This is a plot of a current vs the accelerating potential for varying driving potential. The points of local maxima are denoted with x

Order of the peak	1st	2nd	3rd	4th	5th	6st
Value of U_1						
$U_1 = 1.5$	18,2	36,1	–	–	–	–
$U_1 = 1.6$	17,6	35,15	–	–	–	–
$U_1 = 1.8$	17,6	34,65	39,95	56,55	–	–
$U_1 = 2.02$	17,25	34,3	39,6	53,3	56,2	58,25
$U_1 = 2.30$	16,85	33,85	39,2	52,9	55,8	57,85
$U_1 = 2.50$	16,65	33,95	38,95	52,7	55,6	57,9
$U_1 = 2.70$	16,45	33,7	39,0	52,75	55,6	57,35
$U_1 = 2.90$	16,45	33,45	38,75	52,5	55,4	57,15
$U_1 = 3.30$	15,9	33,2	38,2	52,2	55,1	57,15
$U_1 = 3.60$	15,75	33,05	38,1	51,8	54,7	56,75
Avg	16,87	34,14	38,97	53,09	55,49	57,49

Table 1. Order of the peaks and their value (V) for given driving potential

§ 3: Driving potential 5.00 V, Braking potential – variable

This section is devoted to the data obtained when we set $U_1 = 5.00V$ and let U_3 vary.
Figure 9 shows the data obtained during this stage of the experiment. As before, the different initial conditions are represented by different colours.
Generally, the structure of the curves in Figure 9 is very similar in behaviour to those in Figure 8. In both figures, we see six different local maximums at around the same values of acceleration potential; they also have similar regions of growth and decrease. However, the most significant difference between them is the amplitude and the rate of change. In Figure 9, it is seen that initially, the detected current is zero. However, it starts rapidly increasing after some time, but the growth rate slows down until the first maximum is reached.
It is worth noticing the value of the first maxima's acceleration potential in Figures 9 and 10. Looking at Table 1, we see that the first maxima shifts to the left with the increasing value of the driving potential, but in Table 2, it is seen that the point stays around the value of 14.6 volts (with insignificant fluctuations), independent of the value of the braking potential. So does the first minima (the explanation is given in the Discussion).
After reaching the first minima, the graphs start rapidly rising until reaching a steep peek. As before, the second maximums do not radically vary from the average value. In addition, the second maximums in Tables 1 and 2 are similar but slightly shifted.
As U_2 it increases, the values of the current decrease until reaching the minimum again. However, as in Figure 8, we also observe a slight rise here, corresponding to a third local maxima, followed by a current growth until the 4th maxima is reached.
It's worth noting that there's a significant difference between the curves shown in Figures 8 and 9. However, it's essential to understand that the curves in Figure 9, specifically for the braking potential values of 5.00 V, 5.40 V, and 6.00 V, must provide the complete picture. This is because the fourth, fifth, and sixth peaks went undetected due to the current detector limit being reached before the graphs could reach their maximum value. As a result, further discussion about this difference only applies to these values. The main difference between Figures 8 and 9 curves is the apparent decrease after reaching the fourth maxima. As seen in Figure 8, the last three peaks have approximately the same values of the detected current, so these three points, when taken together, might instead be characterized as a saddle, not a maximum.
In contrast, from Figure 9, the decrease in the value of the current is apparent. Moreover, for the curves corresponding to the braking potential higher than 7.00 V, the fifth and the sixth peaks are not even labelled with x, although they are visible. They are not marked because they are located on a decrease, so they act like saddle points, not as extremums.
After reaching the last minimum, the curves increase again until the end.

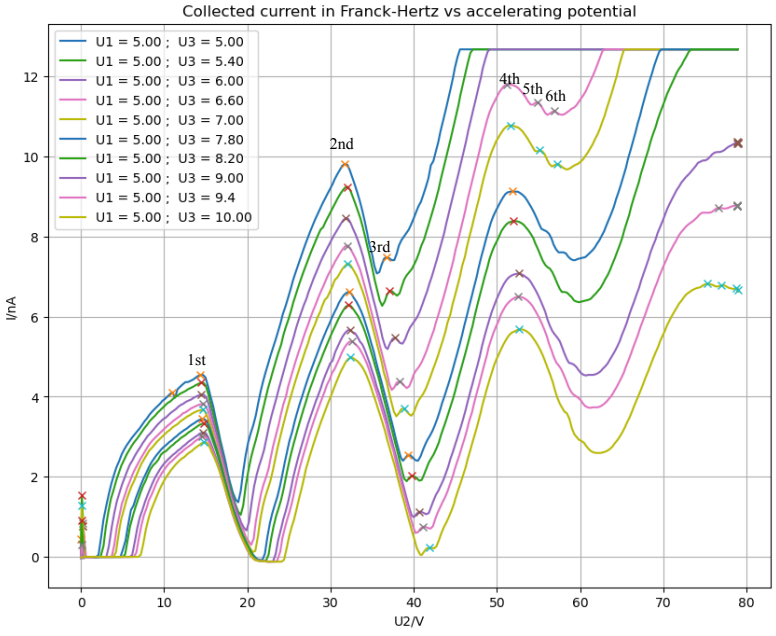


Figure 9. This is a plot of a current vs the accelerating potential for varying braking potential. The points of local maxima are denoted with x

Order of the peak	1st	2nd	3rd	4th	5th	6st
Value of U_3						
$U_3 = 5.00$	14,35	31,7	36,75	–	–	–
$U_3 = 5.40$	14,4	32,05	37,1	–	–	–
$U_3 = 6.00$	14,45	31,85	37,75	–	–	–
$U_3 = 6.60$	14,7	32,05	38,25	51,15	54,9	56,95
$U_3 = 7.00$	14,6	32,0	38,8	51,65	55,15	57,2
$U_3 = 7.80$	14,55	32,2	39,3	51,9	–	–
$U_3 = 8.20$	14,75	32,1	39,75	52,0	–	–
$U_3 = 9.00$	14,7	32,35	40,6	52,6	–	–
$U_3 = 9.4$	14,55	32,55	41,1	52,5	–	–
$U_3 = 10.00$	14,8	32,4	41,85	52,65	–	–
Avg	14,59	32,13	39,13	52,06	55,03	57,08

Table 2. Order of the peaks and their value (V) for given braking potential

§ 4: Excitation energy and the Error analysis

We first want to find Neon's excitation energy. Assuming Bohr's theory is correct, it shows that an atom's excitation energies are discrete values. It is also known that electrons having certain energies colliding with the neon atoms will give the latter the energy (inelastically collide). So, we expect to see the current drop in the values of the accelerating potential corresponding to the excitation energy of the neon atoms. Since the energy of electrons may be found using the expression $\epsilon = eU_2$ if we want to find it in Joules unit, or, more straightforward, using the eV units, the electron's energy is just the value of U_2 (from now on, I will talk about the 'energy' and 'acceleration potential' as about the same thing), then, when electrons reach the energy equal to the excitation energy of the neon atoms they will start losing speed, and thus less of them will reach the anode resulting in lower detected current. The following maximum would arise from the fact that the electron can reach the excitation energy again before leaving the (bc) region. So we would see two equally spaced emissions.

Order of the peak		1st	2nd	4th	Distance between 1st and 2nd	Distance between 2nd and 4th
Value of U_3						
$U_3 = 6.60$		14,7	32,05	51,15	17,35	19,1
$U_3 = 7.00$		14,6	32,0	51,65	17,4	19,65
$U_3 = 7.80$		14,55	32,2	51,9	17,65	19,7
$U_3 = 8.20$		14,75	32,1	52,0	17,35	19,9
$U_3 = 9.00$		14,7	32,35	52,6	17,65	20,25
$U_3 = 9.4$		14,55	32,55	52,5	18	19,95
$U_3 = 10.00$		14,8	32,4	52,65	17,6	20,25
Avg		14,66	32,24	52,06	17,57	19,83

Table 3. Order of the peaks and their value (V) for given braking potential and the distances between the adjacent peaks.

Therefore, to determine neon's excitation energy, we wish to look at the distances between the adjacent peaks (not slight jumps or fluctuations), which, in our case, correspond to the first, second and fourth maximums. However, we need to be cautious because the position of the first peak does not represent the excitation energy since the electrons entering the region (bc) (see Figure 5) have nonzero velocities due to the driving potential. Thus, we need to account for that.

We also wish to perform an error analysis. To find the value of the excitation energy, we will only consider the data from Figure 9. We will only use the curves corresponding to the braking potential of 6.60 V and higher since they provide the complete data, and the current dips are much more pronounced.

As seen from Table 3, the distances between peaks 1 and 2 and between 2 and 4 are unequal. In addition, we must take more than just the average of the values because we first need to account for the errors.

The procedure for determining the errors is as follows:

1. Identify the current and the potential corresponding to the peak.
2. Find points around the peak.
3. If we have the same peak current for different U_2, we take an average of the latter to be the peak potential used.
4. The difference in the potential corresponding to the same value of current before and after the peak divided by two will be an error. (Mean value theorem guarantees that there exists a maximum between those points)

Current (nA)	Acceleration voltage (V)
3,765	13,8
3,795	14,1
3,81	14,4
3,825	14,7
3,765	15
3,63	15,3
3,42	15,6

Table 4. Current (nA) vs Acceleration voltage (V) around the peak of the curve corresponding to $U_3 = 6.60V$

An example with the data set corresponding to $U_3 = 6.60V$. Table 4 shows the data points around the first maximum. It is seen that the nearest identical current values are for $U_2 = 13.8V$ and $U_2 = 15V$. Therefore, we may conclude that the error in measuring the peak voltage is $\frac{15 - 13.8}{2} = 0.6$. Thus, the first peak is at $14.7 \pm 0.6V$.

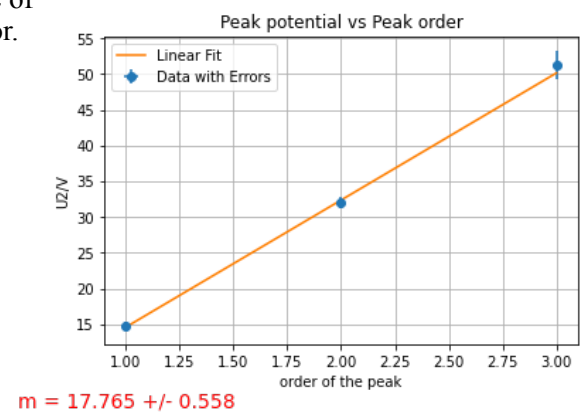


Figure 10. Graph of the peak potential vs order of the peak. m here represents a slope and ± represents an uncertainty of the slope

We repeat the same procedure for all three peaks and then plot the peak potential vs the peak order (it would always be 1, 2, 3 since we only have three apparent maximums). We then do a least square fit, and the slope of the graph would be the value of the neon's excitation energy (See Figure 10). We may also obtain an uncertainty corresponding to the obtained value (Summing the squares of all errors and taking a square root). In the end, the average of the slopes will represent the excitation energy, and the average of the uncertainties will represent the uncertainty with which we expect the result to be accurate. Table 5 shows all these values for the given braking potential and their uncertainties.
From Table 5, we may conclude that neon's excitation energy is

$$\epsilon = (18.71 \pm 0.557)\ \text{eV} \tag{3.}$$

compared to if we just took the average from Table 3 and got $\epsilon = 18.7$ eV

Order of the peak		1st	2nd	4th	The slope (i.e the excitation energy)	Uncertainty
Value of U_3						
$U_3 = 6.60$		14,7	32,05	51,15	17,765	±0,558
$U_3 = 7.00$		14,6	32,0	51,65	18,478	±0,285
$U_3 = 7.80$		14,55	32,2	51,9	18,675	±0,279
$U_3 = 8.20$		14,75	32,1	52,15	19,196	±0.899
$U_3 = 9.00$		14,7	32,35	52,6	18,956	±0,294
$U_3 = 9.4$		14,725	32,55	52,65	19,616	±0,769
$U_3 = 10.00$		14,8	32,4	52,775	18,304	±0.812
Avg					18,71	±0,557

Table 5. Order of the peaks and their value (V) for given braking potential and the found value of the excitation energy and the uncertainty.

If we also wanted to use the data in Figure 8 without accounting for any errors, we could build a table similar to Table 3 and find an average distance between the peaks. Table 6 shows the peaks and the distances between them, using data from Figure 8. As a result, we find that the excitation energy is $\epsilon = 18.2$ eV, which is, surprisingly, within the error range of equation 2.

Order of the peak		1st	2nd	4th	Distance between 1st and 2nd	Distance between 2nd and 4th
Value of U_1						
$U_1 = 1.8$		17,6	34,65	56,55	17,05	21,9
$U_1 = 2.02$		17,25	34,3	53,3	17,05	19
$U_1 = 2.30$		16,85	33,85	52,9	17	19,05
$U_1 = 2.50$		16,65	33,95	52,7	17,3	18,75
$U_1 = 2.70$		16,45	33,7	52,75	17,25	19,05
$U_1 = 2.90$		16,45	33,45	52,5	17	19,05
$U_1 = 3.30$		15,9	33,2	52,2	17,3	19
$U_1 = 3.60$		15,75	33,05	51,8	17,3	18,75
Avg		16,61	33,77	53,09	17,16	19,32

Table 6. Order of the peaks and their value (V) for given driving potential and the distances between the adjacent peaks

Discussion

§1: Source of errors

Based on the obtained result (3.), the error is just 2.97% of the obtained value. This error might not seem to be critical. However, in the quantum world, this error might result in incorrect data interpretation. In order to make any conclusions, we first need to analyze the source of an error and answer a simple question: Should the energy within the error be greater than 18.7 or smaller?

There are three sources of error that we need to examine. The first reason is physical and is related to the postulates of quantum mechanics. According to the Heisenberg uncertainty principle, we cannot know the position and momentum of a particle with the same precision. Similarly, we cannot measure the energy and time with the same level of accuracy. Although this could have caused an error in our experiment, it would have been negligible if we dealt with a small percentage. Therefore, we can disregard this reason and focus on the remaining two sources of error.

The second reason is physical and relates to the free path length of electrons. The free path length refers to the maximum distance an electron can travel without interacting with anything. We can calculate this value using the density of the gas and the velocity distribution of the electrons. However, it is impossible to calculate this value for every single electron, so we only focus on the average free path length. As a result, we have a distribution with its own errors. Therefore, when we detect a peak, we can only say that most of the electrons have reached the required energy for excitation. However, in reality, the peak could have been reached earlier, but not all electrons collided with atoms at that point. The statistical nature of the experiment accounts for part of the error. The actual excitation energy should be slightly lower than the value obtained to correct this.

The final reason for the error is instrumental, accounting for most of the problem. The issue arises due to the frequency of measurements taken. As per the error calculation method mentioned in §4 Results, increasing the frequency of measurements would provide more data points and thus enable us to determine the position of the peak with greater precision. Unfortunately, we cannot account for this reason in the error since changing the detection rate would only narrow down the peaks' position.

Based on the above arguments, an actual excitation energy should be slightly smaller than (3.).

§ 2: Is Bohr's quantization correct?

As discussed in § 2 of the introduction, Bohr derived that electrons in atoms can only occupy discrete energy levels. For neon atoms, it was found that excited energy levels correspond to the energies (Kaur, 1999) in Table 7. Note that the obtained result (3.) with the error correction (see above) fits the predictions and the neon's structure (Figure 7) and corresponds to the $2s^2 2p^5 (^2P^0_{3/2}) 3p$ configuration. We can conclude that Bohr's quantization is valid since the data fits the theory!

Configuration	Term	J	Level (eV)
$2s^2 2p^6$	$2p^6\ ^1S$	0	0.000 00
$2s^2 2p^5(^2P^o_{3/2})3s$	$3s[3/2]^o$	2	16.619 07
		1	16.670 83
$2s^2 2p^5(^2P^o_{1/2})3s$	$3s'[1/2]^o$	0	16.715 38
		1	16.848 05
$2s^2 2p^5(^2P^o_{3/2})3p$	3p[1/2]	1	18.38162
		0	18.711 38
$2s^2 2p^5(^2P^o_{3/2})3p$	3p[5/2]	3	18.55511
		2	18.575 84
$2s^2 2p^5(^2P^o_{3/2})3p$	3p[3/2]	1	18.61271
		2	18.636 79
$2s^2 2p^5(^2P^o_{1/2})3p$	3p'[3/2]	1	18.693 36
		2	18.704 07
$2s^2 2p^5(^2P^o_{1/2})3p$	3p'[1/2]	1	18.726 38
		0	18.965 96

Table 7. Energy levels corresponding to their configuration

§ 3: Slight problem

As was shown above, the obtained result for neon's excitation energy is $\epsilon = (18.71 \pm 0.557)$ eV. According to Bohr, the excited levels are not stable, so the electron will fall back to the ground state, emitting the photon of the frequency.

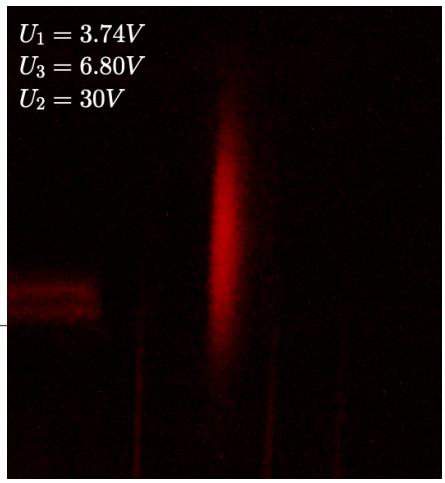
$$\nu = \frac{\epsilon}{h}$$

If we instead wish to know the corresponding wavelength, we may use the Planck – Einstein relation :

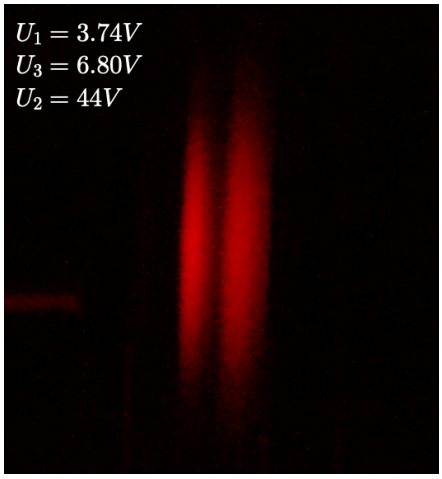
$$\lambda = \frac{hc}{\epsilon} \quad \text{(keeping in mind that } \epsilon = eU\text{)}$$

So, according to our measurements, we should get the emission of the radiation with a wavelength of 66.26 nm, which corresponds to UV light. However, this result does not match the observations. Figure 11 shows the emission light (the initial conditions were chosen only based on light intensity). The light we see is in the observable spectrum and, more importantly, appears to be orange. Where does the inconsistency between the observation and the theory originate from?

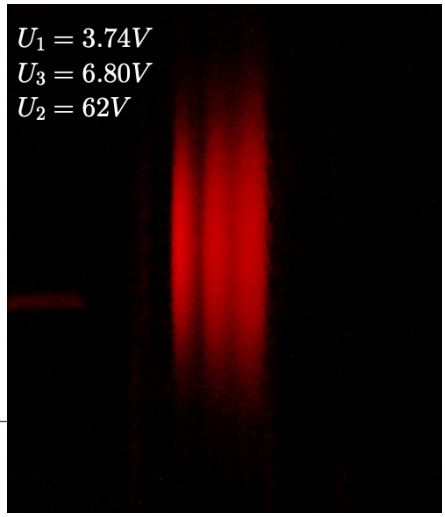
The answer to the question lies down in the structure of neon. If we try to find the photon's energy corresponding to the orange light (585 – 620 nm), we get a 2.12 to 1.99 eV range. Moreover, the distance between $2s^2 2p^5(^2P^0_{3/2})3p$ and $2s^2 2p^5(^2P^0_{3/2})3s$ is precisely 2.03 eV, corresponding to an emitted light of 610.79 nm, which is orange. Therefore, we may conclude that $2s^2 2p^5(^2P^0_{3/2})3s$ is a metastable state and the electron, before returning to the ground state, passes through this metastable state and emits light photons. So, the theory is indeed correct!



a.)



b.)



c.)

Figure 11. Visible light detected for given conditions corresponding to the peaks: a.) – first peak; b.) – second; c.) – third

§ 4: Further discussion on the curves' behaviour

In both Figures 8 and 9, the initial growth rate is much higher than at any subsequent times. The reason is that for low accelerating potential, electrons do not have enough energy to overcome the braking potential but cannot come back to the cathode due to the direction of E_2. So they get stuck on the control grid until the accelerating potential is high enough that passing electrons can inelastically collide with the 'stuck' ones and simultaneously reach the anode, resulting in a high current jump (since the current is a number of electrons times their charge over time). When there are no electrons left on a cathode grid, the growth rate slows down.

It is essential to consider the depth of the wells and the width peaks. The difference between Figures 8 and 9 is apparent in this context. Based on the collected data, we can conclude that higher driving potentials result in deeper wells, and the current deeps are more pronounced. The physical reason for this phenomenon is that higher values of driving potential lead to a higher electron flux, as more electrons can overcome the bonding energy at higher potentials. The width of the peaks can be related to the probability of electrons inelastically colliding with neon atoms, making the peaks look sharper for higher driving potential.

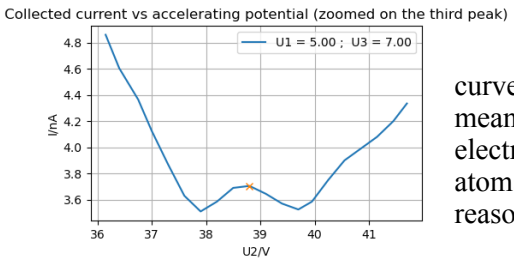


Figure 12. 3rd peak zoomed in

Lastly, the appearance of the minor peaks (3rd, 5th and 6th) is worth mentioning. Figure 12 shows the third peak for one of the curves. Physically, the appearance of such jumps means that at the expected minimum value, electrons stop inelastically colliding with neon atoms, and the current increases. The possible reasons might include the impurities of neon (it was mixed with other gases) or the detector errors. Unfortunately, the rigorous search for the reasons goes beyond the scope of the paper. However, it might be worth explaining this effect in future work.

§ 5: Future research

There are a few possibilities for future research. First, as mentioned in § 1 of this section, the error might be minimized by adjusting the detection rate. Second, in order to obtain the best results for the energy levels, the spectrometer can be used. In this way, the measurement of the wavelength would be more precise, and the energy states could be determined in a more accurate manner.

The best future research would be the investigation of the statistical phenomenons discussed in (Robson 2014). The statistical approach they take is far more rigorous than the approach used here. They describe and explain why during the inelastic collisions, the electrons in neon atoms skip all the energy levels before reaching e $2s^2 2p^5(^2P^0_{3/2})3p$. This is an extremely interesting phenomenon, which is related to the maximum cross-section of the configurations.

Conclusion

This paper explores the fundamental structure of nature - atoms. Over the course of human history, numerous theories and models of atomic structure have been proposed. However, each time a theory was created, new observations would reveal something different, leading to the theory being modified and rebuilt. In the early 20th century, Niels Bohr proposed the planetary model and the theory of energy quantization. Although the model had to be rebuilt due to the development of quantum mechanics, Bohr's energy quantization theory remained unchanged. In 1914, James Franck and Gustav Hertz demonstrated that this theory is applicable to mercury vapour. In this paper, we have replicated this hundred-year-old experiment using neon gas.

In order to obtain accurate results, we studied the properties of neon atoms and how the quantization theory predicts the outcomes of the experiment. During our research, we found that if Bohr's theory is correct, then we should measure the excitation energy as one of the possible values listed in Table 7 and Figure 7.

To study the excitation energy of neon gas, we utilized the apparatus shown in Figure 5. The driving potential allowed electrons to escape the cathode and travel into the 'drift region'. There, they were accelerated by a varying potential. Once the electrons passed the second control grid, the electric field slowed them down. This meant that only electrons with enough energy could pass through to the cathode, where we could detect a current flow. According to Bohr’s theory, the detected current would decrease when electrons reach the energy equal to one of the neon’s excited energy levels.

We found that the excitation energy was (18.71 ± 0.557) eV, which matched the values in Table 7. However, we discovered an issue when the predicted radiation wavelength was supposed to be in the ultraviolet region, but the detected radiation was visible to the naked eye. To solve this, we introduced the metastable state in neon, where the excited electron falls before returning to the ground state. After analyzing our findings, we concluded that Bohr's theory was correct.

This result is of great importance as many quantum theories operate on this principle. One of the major applications is in lasers, which use the theory of energy quantization as their principle. Lasers are widely used, from classroom pointers to the development of fusion reactors which might become the main source of future energy.

There is plenty of potential for enhancing and adjusting this experiment. One option could be to utilize the spectrometer for analyzing the wavelength of the emitted radiation. Additionally, it is possible to take a more comprehensive approach and evaluate the results statistically.

References

1. Pullman, B. (1998). The Atom in the History of Human Thought. Oxford, England: Oxford University Press. https://books.google.ca/books?id=IQs5hur-BpgC&q=Leucippus+Democritus+atom&pg=PA56&redir_esc=y#v=onepage&q&f=true

2. Dalton, J., & Thomson, T. (1970). Atomic theory. New York: Doubleday. https://upload.wikimedia.org/wikipedia/commons/3/32/Foundations_of_the_atomic_theory_-_comprising_papers_and_extracts_(IA_b21901958).pdf

3. Pestka, J. (2017). "About Rutherford's Gold Foil Experiment". https://sciencing.com/rutherfords-gold-foil-experiment-4569065.html

4. Scherrer, R. J. (2005). Quantum Mechanics: An Accessible Introduction (pp. 17-20). Benjamin Cummings.

5. Bohr, N. (1913). I. On the constitution of atoms and molecules. The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science, (151), 1–2.

6. Franck, J. (1926, December 11). Transformations of kinetic energy of free electrons into excitation energy of atoms by impacts [Nobel Lecture].

7. Kaur, Savinder & Srivastava, Rajesh & Mceachran, Robert & Stauffer, Allan. (1999). Excitation of the np5(n+1)p (J = 1, 2 and 3) states of the inert gases by spin-polarized electrons: integrated state multipoles and Stokes parameters. Journal of Physics B: Atomic, Molecular and Optical Physics. 32. 4331. 10.1088/0953-4075/32/17/316.

8. Robson, R. E., White, R. D., & Hildebrandt, M. (2014). One hundred years of the Franck-Hertz experiment. The European Physical Journal D.