Determining the excitation energies of mercury and neon using Franck-Hertz tubes

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Second Year Laboratory Report

Nov 2014

Abstract

The excitation energies for mercury and neon were determined using Franck-Hertz tubes filled with the mercury vapour and neon gas, respectively. The energies were obtained as the distance between successive peaks in the electron current plotted against the electron's acceleration voltage. We found ΔE_{Hg} to be (5.08 ± 0.43) eV and ΔE_{Ne} to be (18.85 ± 2.09) eV.

1. Introduction

In the first two decades of the twentieth century, the early formalisms of the quantum theory, such as Bohr's model of the atom, all pointed to discrete energy levels. The development of quantum theory was made possible through experimental results on atomic energy levels. An important experiment which established discrete energy levels was the so-called Frank-Hertz experiment.

In their experiment, Frank and Hertz found the energy absorbed during inelastic collision of electrons with mercury atoms assumes discrete values. These values correspond to the gaps between energy levels of the electrons. [1]

2. Theory

In the Franck-Hertz experiment, electrons are accelerated using a small electrostatic potential difference. The electric field due to the potential difference could reasonably be considered constant and homogeneous. With this approximation, the field generated by a voltage V across a tube of length D, will be

$$E = \frac{V}{D}. \tag{1}$$

The kinetic energy of an electron after travelling a distance x is given by the work done by the electric field [2],

$$T(x) = \frac{eVx}{D}. \tag{2}$$

Naturally, the electrons will have some elastic collisions with the atoms in the tube. The question explored by the experiment is that of inelastic collisions which cause the transfer of energy from the free electrons to the electrons in the target atoms. An inelastic collision by free electrons means that they will lose their kinetic energy and may not reach the end of the tube resulting in a drop in the current.

According to the Bohr model of the atom, which was proposed a year before the historical experiment, the energy levels of electrons in an atom are quantised and assume discrete values that depend on the principal quantum number n,

$$E = -13.6\frac{Z^2}{n^2}eV, \tag{3}$$

where Z is the number of protons within the atom.

Quantised energy levels have the implication that atoms can absorb the electrons energy only at certain quantised values that represent the difference between two energy levels. This was beautifully confirmed by the Franck-Hertz experiment. As the electrons travel and reach an energy equal to 4.9 eV (the energy gap between the two lowest energy levels of mercury), the inelastic collisions start and the current drops. As the potential is increased, the electrons reach this energy at shorter distance, as expressed by Eq. (2) and can undergo more than one inelastic collision.

3. Experimental Method

3.1. Diagram of Experiment

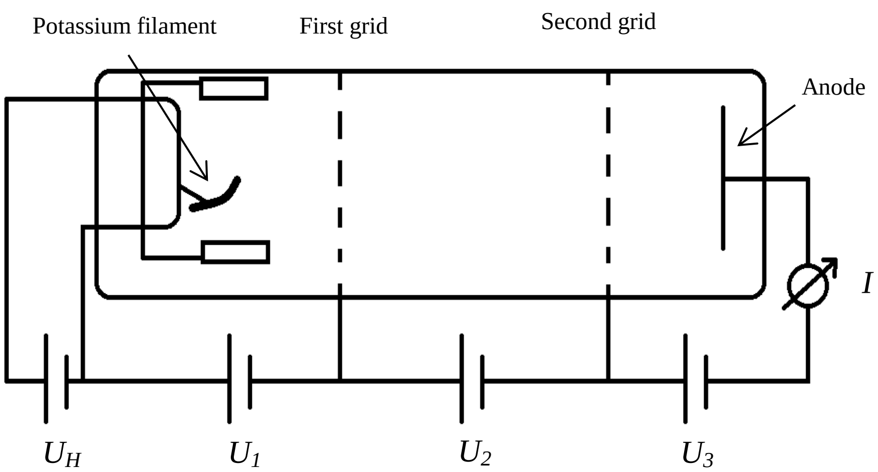

Figure 1. Schematic view of a Franck-Hertz tube.

3.2. Method

A Franck-Hertz tube, filled with mercury vapour at low pressure, was placed in a heating chamber and connected to an electronic thermometer, power supply and a graph plotting machine. The temperature of the tube could then be controlled using the power supply. The temperature was set to 150^{o}C and given time to warm up. Initially, the grid voltage and stopping voltage (U_1 and U_3) were set at 1.5v. The accelerating voltage (U_2) was varied and the plotting machine produced a graph showing the current flowing through the tube's anode. Measurements of current were taken over the range 0V – 32V. This process was then repeated, in increments of 10^{o}C, from 150^{o}C - 180^{o}C. The locations of minimum current were judged by eye and the values of U_2 at which they appear on the graph were recorded. The potential differences could then be calculated by subtracting these voltages.

A new graph was taken for a tube filled with neon gas at room temperature. The stopping voltage was increased to 10.25V to make the changes in current more visible; since a low stopping voltage meant that no more than one peak could be seen.

4. Experimental Results

4.1. Observations of the graphs

Five graphs were obtained for mercury and one for neon.

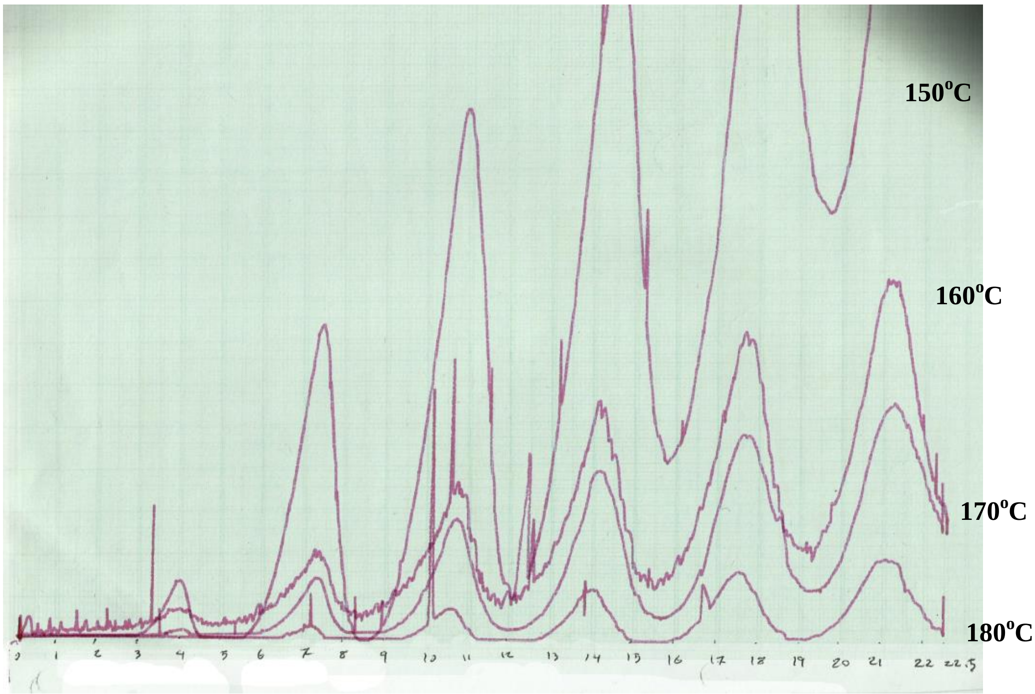

Figure 2. Curves obtained for mercury vapour at various temperatures.

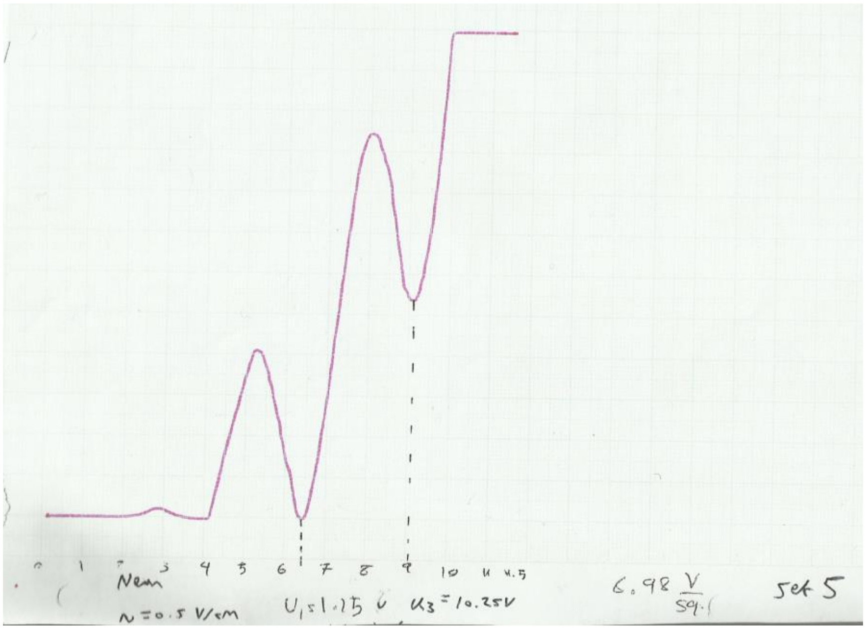

Figure 3. Curve obtained for neon gas at room temperature.

It can be seen that the graph follows a repeating pattern of the current rising to a maxima and then falling to a minima. The rise is simply due to increased electron speeds decreasing the time crossing the tube and leading to an increase in the current. This falls to a minimum when the electrons have enough energy to excite a mercury atom in an inelastic collision, resulting in reduced kinetic energy and an inability to overcome the stopping potential at the anode. This process then repeats when the electrons can be accelerated enough to have further inelastic collisions after the first collision. Evidence for discrete energy levels comes from the fact that these minima are all equally spaced, with this spacing being the excitation energy of the mercury.

It can also be seen that increasing the temperature of the tube decreases the amplitude of the current. An increased temperature will increase the random motion of the gas particles. As a consequence, the electrons will undertake more inelastic collisions while travelling through the tube. Therefore, electrons will take longer to reach the anode and a smaller current will be measured.

4.2. Calculating the excitation energies

A table of results was recorded, as shown in Appendix A. The average of the fifteen measurements for mercury gave a value of 5.08eV for the excitation energy. As only two peaks were observable for neon, there was only one potential difference of 18.85eV. The dominant error in the experiment was the human error of judging where minima occurred on the graph and then reading their values off the scale. We estimated the uncertainty on this to be a width of three minor squares, which equates to a voltage of 0.43eV for mercury's graphs and 2.09eV for the neon graph. Leading to final values of (5.08 ± 0.43) eV and to be (18.85 ± 2.09) eV for mercury and neon, respectively.

5. Conclusion

The Franck-Hertz experiment was reproduced using mercury vapour at controlled temperatures ranging from 150 to 180 degrees Celsius. The current passing through the tube was plotted as a function of acceleration voltage across the tube. As expected from the quantum theory, the curve displayed a distinct pattern of minima at intervals corresponding to the energy gap between the accessible levels of mercury atom. The energy gap was measured as (5.08 ± 0.43) eV, which is within one standard deviation from the best value of 4.9eV. The procedure was repeated for neon gas at room temperature and the same pattern was observed with the energy gaps set at (18.85 ± 2.09) eV, which is again, in agreement with the best value. However, due to the error of about 2 eV it was clearly not possible to resolve the fine structure of neon. [3]

Acknowledgments

We'd like to thank our lab demonstrator for instruction on best use of the apparatus.

References

[1] S. Brandt, The Harvest of a Century: Discoveries in Modern Physics in 100 Episodes, Oxford University Press, 2008

[2] John D. Jackson, Classical Electrodynamics, John Wiley & Sons Ltd. 1962

[3] R. Nave, Franck-Hertz Experiment, HyperPhysics, Accessed on 17/11/2014, URL: http://hyperphysics.phy-astr.gsu.edu/hbase/frhz.html

[4] Niels Bohr, "Atomic Structure". Nature 107 (2682). 1921

Length and Date

The number of words in this document is 1191

This document was printed on 18/11/2014 at 19:40.

Appendix A

Gas in the Franck-Hertz tube	Temperature (^{o})	U_2 (eV)	ΔU_2 (eV)
Mercury	150	7.100	
		11.928	4.83
		17.040	5.11
		22.294	5.25
		27.832	5.54
	160	7.100	
		12.070	4.97
		17.040	4.97
		22.152	5.11
		27.335	5.18
	170	6.750	
		11.790	5.04
		16.760	4.97
		22.010	5.25
		27.120	5.11
	180	12.070	
		17.040	4.97
		22.010	4.97
		26.980	4.97
Neon	Room temperature (uncontrolled)	44.670	
		63.52	18.85

Table 1. Measured minima voltages for the Franck-Hertz tube with mercury heated at various temperatures and neon at a fixed temperature that was set for us.