

EXPERIMENT 5

The Franck-Hertz Experiment (Critical Potentials)

Introduction

In the early part of the twentieth century the structure of the atom was studied in depth. In the process of developing and refining a theory of atomic structure, scientists developed a number of theories and techniques designed to explain and investigate experimental atomic phenomena.

Scientists had developed a periodic table of the known elements without realizing the part that the structure of atoms played in placing an element in that table. It had been found that atoms are related to electromagnetic phenomena, since molecules could be dissociated into their component elements by applying a current to them. The differences among magnetic, insulating and conducting materials were suspected to be related to atomic structure. Heated elements emitted light when a current passed through them. The light emitted by elements is at specific frequencies which indicated a characteristic internal structure specific to each element.

In 1897, J.J. Thomson developed a technique to deflect charged particles through magnetic fields. This technique provided indications about the charge-to-mass ratio and sign of the charge of an electron. In 1909, Ernest Rutherford, Hans Geiger and Ernest Marsden developed scattering experiments to probe the internal charge and mass distribution of atoms. In 1915, Niels Bohr developed mathematical techniques for predicting atomic behaviour that incorporated the new ideas of quantization and correlated to experimental analysis of the wavelength spectra of hydrogen.

Making quantum theory fit the experimental data led to refinements in understanding the atomic structure. For example, Bohr's calculations of the wavelength of hydrogen's spectra were slightly different from the experimental results. Resolving the differences led to the understanding that the electron does not simply revolve about the hydrogen nucleus, but both revolve around their combined center of mass.

Prior to the experiments performed by James Franck and Gustav Hertz, the quantum theory had been applied to atoms to describe radiation of photons only. Franck and Hertz decided to study electrons, atoms, and the transfer of kinetic energy. Their experiment extended the application of quantum theory to electrons and their energy levels, and provided a new technique for studying atomic structure. In this practical you will carry out a variant of the Frank-Hertz experiment to determine the critical potentials of the atoms in a gas of He or Ne.

Theory

In the kinetic theory of gases, it is assumed that the atoms of a gas are hard, perfectly elastic spheres. The atoms collide elastically with each other, and with the walls of the containing vessel. In this picture, the pressure the gas exerts on the walls of the containing vessel is equal to the momentum transferred to unit area of the wall per unit time. The average kinetic energy of an atom or molecule of gas is given by $\frac{3}{2} kT$, where k is Boltzmann's constant and T is the absolute temperature. The total energy of N molecules is then $\frac{3}{2} NkT$. If we rewrite in terms of the number of moles, n , then the total energy of n moles is $\frac{3}{2} nRT$ where $R = k \cdot N_A$ is the Universal gas constant = 8.315 J/(mol.K) and N_A is Avogadro's number. Hence the total kinetic energy per mole of gas is

$$\frac{3}{2} RT \quad (5.1)$$

Now, it is found experimentally that the specific heat of a mole of monatomic gas is

$$\frac{3}{2} R$$

Comparing this with Eq. 5.1, one can conclude that the energy supplied to increase the temperature of one mole of monatomic gas by 1K, i.e. $\frac{3}{2} R$, goes solely to increasing the kinetic energy of the atoms. The agreement between results of the kinetic theory of gases and experiment lends strong support to the assumption that an atom can be regarded, in many instances, as a perfectly elastic, hard sphere.

Experiments carried out at the beginning of the 1900's indicated that atoms are made up of nucleons and electrons. If so, one would expect that when one atom of gas collides with another, or with the walls of the containing vessel, some of its kinetic energy would go into internal energy of the atom, i.e. to increasing the motion of its constituents. In that case, the collision would not be elastic, in disagreement with the kinetic theory.

This apparent contradiction can be overcome if the internal energy of an atom cannot have arbitrary values, but only certain quantized, or discrete, values. This could be represented, diagrammatically, by an energy level diagram (Fig. 5.1).

The state of the lowest internal energy of an atom is called the ground state, and the energy of this state can be denoted by E_0 . E_1 is the energy of the first excited state, E_2 the energy of the second, etc. The atom cannot exist with an energy intermediate between E_0 and E_1 , or E_1 and E_2 etc. E_∞ is the energy of the ionized atom, i.e. an atom with an electron removed completely from it. For reasons which will become clearer later, $E_1, E_2, E_3,$ etc. are called the excitation potentials, and E_∞ the ionization potential of an atom, when they are expressed in electronvolts. The atom will normally exist in the state of lowest energy, i.e., the ground state. To raise it from the ground state to the first excited state, an amount of energy ($E_1 - E_0$) must be supplied. In the case of atoms in a gas, this energy must come from the kinetic energy of the atoms, which could become internal energy in a collision. The mean kinetic energy of an atom in a gas at temperature T is

$$\text{Mean kinetic energy} = \frac{3}{2} kT$$

At 300 K, this is equal to 2.6×10^{-2} eV. If ($E_1 - E_0$) is much greater than 2.6×10^{-2} eV, then the atoms will behave elastically in collisions. We would hope to find ($E_1 - E_0$) if we pass electrons

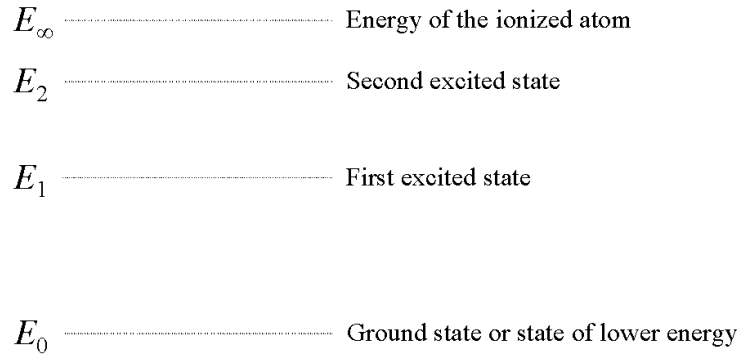


Figure 5.1: Schematic energy level diagram of an atom.

of variable energy through the gas and detect the energy at which they raise the atoms with which they collide to the first excited state. This forms the basis of the present experiment, which was first performed by Franck and Hertz in 1914 and is an experimental verification of the fact that the internal energy of an atom is quantized.

Experimental Apparatus

Tube Description

The Critical Potentials tube (TEL 2533) consists of a simple diode gun which emits a divergent beam of electrons into a clear glass bulb containing either helium or neon gas at low pressure (Fig. 5.2). Electrons are emitted thermionically from a heated tungsten filament housed in the gun's cathode can. Located inside the bulb is a wire ring collector positioned so that it cannot receive electrons directly from the electron beam; this ring is connected to a screened lead terminated with a BNC plug. The inside surface of the glass bulb is coated with a transparent conducting layer which is insulated from the wire ring but connected to the anode of the diode gun.

Tube Operating Specification

- Filament voltage (V_F): 3.0 V dc max. (IMPORTANT: Never exceed this maximum voltage, as this would damage the tube !!)
- Anode voltage (V_A): 0 - 50 V dc (60 V max.)
- Anode current (I_A): 10 mA max.
- Collector voltage (V_C): ± 1.5 V dc, dry cell battery, AA type
- Collector current (I_C): 0 to ± 200 pA

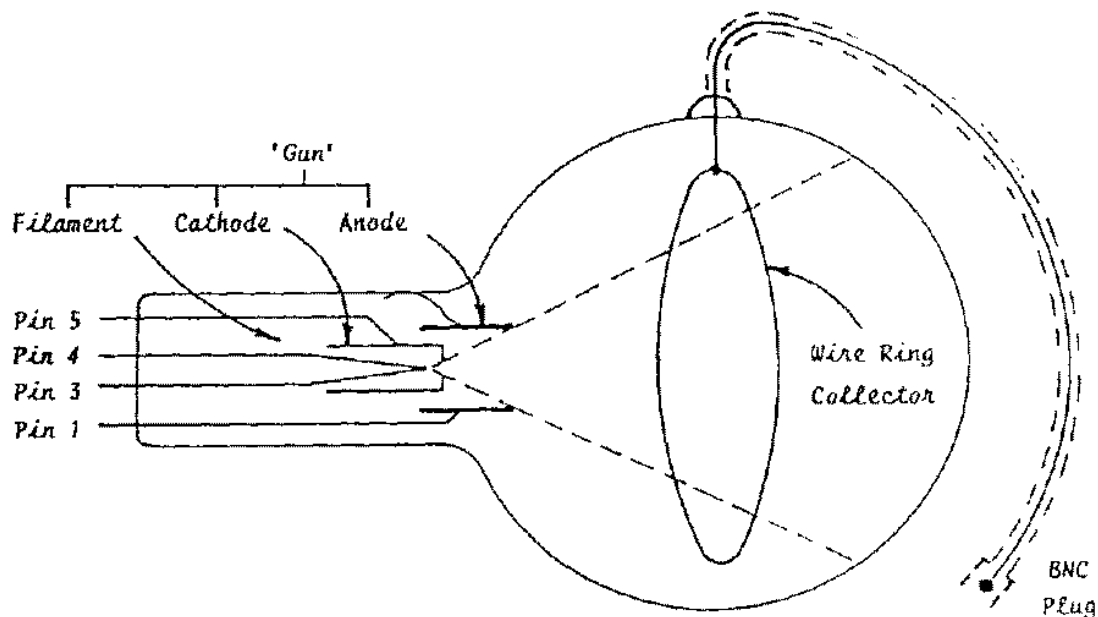


Figure 5.2: Schematic of the Critical Potentials tube (TEL 2533).

Tube Function

The electrons emitted from the diode gun are accelerated through a potential $+V_A$. Some electrons travel straight to the anode to give rise to the anode current I_A , but a significant proportion are projected through the cylindrical anode to enter the spherical glass bulb containing the gas. As the electrons pass through the bulb, they collide with the gas atoms in their path.

If the kinetic energy of an electron is less than the lowest excitation level for the gas atom, the collision is elastic and no energy is lost to the more massive gas atom. This electron traverses the bulb to impact with the conductive coating and returns to the anode, thus contributing to the anode current I_A . An electron with just sufficient energy to excite an atom will, after (inelastic) collision, have little or no residual energy and, in the field-free region of the bulb, would diffuse eventually to the conductive coating of the walls, contributing to the current I_A . However, by making the ring collector a few volts positive ($+V_C$) with respect to the anode, such an electron will be attracted to it and 'collected'. Thus, when the mean energy of the electron stream is sufficient to excite the gas atoms, the population of low energy electrons will increase significantly to produce, in the collector, a measurable current (I_C) with little or no contribution from the main stream. As the accelerating voltage is increased, the excitation at first increases, and then falls away until another higher energy excitation occurs, resulting in a further increase in the low-energy electron current. A further increase in the accelerating voltage results in the ionisation of the atoms. This leads to the liberation of more electrons in the tube, resulting in a steady increase of the current in the collector.

Experiment 5. The Franck-Hertz Experiment (Critical Potentials)

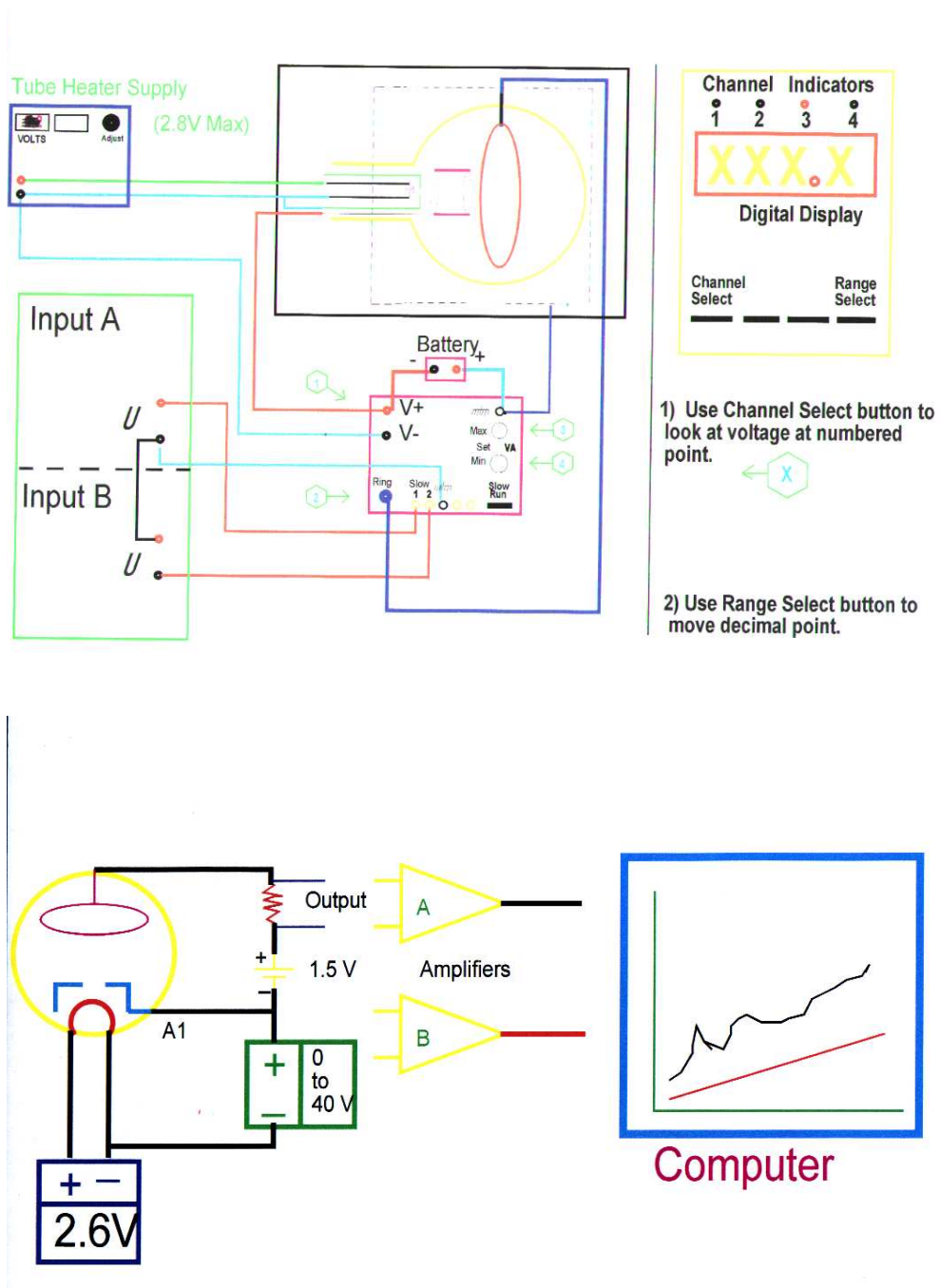


Figure 5.3: Experimental circuit diagrams.

Experimental Procedure

Set up the experiment according to the circuit diagram shown in Fig. 5.3, making sure the filament voltage (V_F) is at zero. Slowly increase V_F in the region 1.5 to 2.6 V. For typical experiments carried out with this apparatus V_F was set at 2.6 V. Under no circumstances should V_F exceed 3 V, as this could damage the tube.

The Hertz Control Console (TEL 2812) supplies the anode voltage, V_A , at Channel 1 as a saw tooth ramp of frequency 20 Hz; this voltage is externally metered using a digital meter (TEL 2021) and is variable from 0 to 60 V. The TEL 2021 digital meter allows the maximum and minimum scan voltages to be set at Channels 3 and 4 respectively. The ramp is activated by an illuminated RUN press-button.

The cable from the collector ring is connected to an integral ac amplifier via a BNC socket, and the current (I_C) is monitored (200 pA max.) at Channel 2.

The 0-1 V OUTPUTS present both the anode voltage ramp (V_A) and the I_C/V_A characteristic in SLOW form, for output to a data recorder, and in FAST form, for analysis with an oscilloscope. In this experiment, the SLOW form output is directed to a CASSY-Lab data recorder, which enables the output to be visualised and analysed using a PC.

Data acquisition

Note: Before proceeding with this section, familiarise yourself with the CASSY-Lab software.

Exploratory scan

In the TEL 2021 meter, set the minimum (V_M) and maximum anode voltages to 10 and 50 V, respectively, to carry out an exploratory scan as illustrated in Fig. 5.4. Using the CASSY-Lab software, overlay plots of the anode voltage ramp (V_A) and the I_C/V_A characteristic versus time. In order to do this, make sure that the red indicator in the Hertz Control Console is illuminated, showing that the SLOW RAMP mode is in the off condition. To record a scan, simultaneously press the RUN button (the red indicator will become green whilst the acquisition is in progress) on the Control Console and the acquisition icon in the CASSY-Lab program. Carefully adjust the filament voltage (V_F) slightly taking care not to exceed 3 V until the response trace resembles that illustrated in Fig. 5.4.

Take note of the times (x-axis) corresponding to the two features shown in Fig. 5.4 (i.e. V_1 and V_R). Taking into account that the acquisition-time spans from 0 to 25 s, use the minimum and maximum anode voltages to derive a calibration factor in V/s. Using this factor, calculate the values of V_1 and V_R in volts.

Upper and lower critical regions

Scan the lower part of the critical region by changing the minimum and maximum anode voltages to the values shown in Fig. 5.5, depending on the tube used i.e. between 15 and 25 V for He and between 10 and 22 V for Ne. Take note of the positions of features V_1 to V_8 in the x-axis (time). Derive a new calibration factor to calculate the values of these features in volts. Repeat the

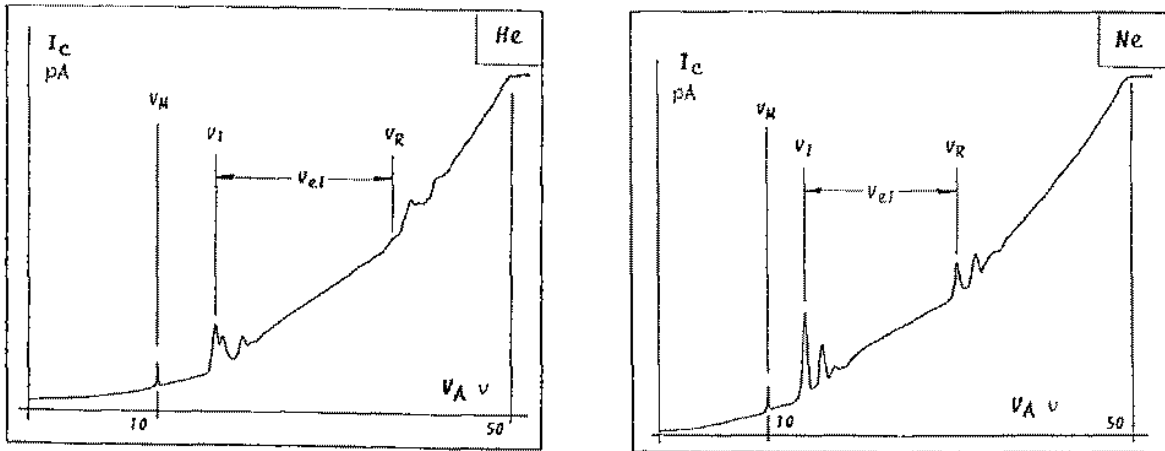


Figure 5.4: The exploratory scan.

Table 5.1: Principal energy levels of Helium and their critical potentials. The 1^1S level is assumed to be at 0 eV.

		2^1S - 20.61 eV	3^3S - 22.71 eV	Ionisation potential
	2^3S - 19.80 eV	2^3P - 20.96 eV	3^1S - 22.91 eV	
		2^1P - 21.21 eV	3^3P - 23.00 eV	
			3^1P - 23.08 eV	
Averages	19.8 eV	20.9 eV	22.9 eV	24.6 eV

procedure for the upper part of the critical region (Fig. 5.6). Again derive a new calibration factor to calculate the value of V_R in volts.

Data analysis

In the lower critical region scan (Fig. 5.5), features V_1 to V_7 correspond to different transitions from the ground state to excited levels in the atom (Fig. 5.7 and Table 5.1). Electrons emitted from the diode gun have the exact amount of energy to excite an atom to different levels when the accelerating voltage V_A satisfies the following equation

$$E_{n'} - E_{n''} = V_A + V_O \quad (5.2)$$

where V_0 is the energy required to extract the electrons from within the filament to its surface.

The maximum amount of energy the atom can absorb is that required to remove an electron completely beyond the influence of the nucleus

$$E_\infty - E_{n''} = V_{A\infty} + V_O \quad \text{and} \quad E_\infty \text{ is zero by convention.}$$

Experiment 5. The Franck-Hertz Experiment (Critical Potentials)

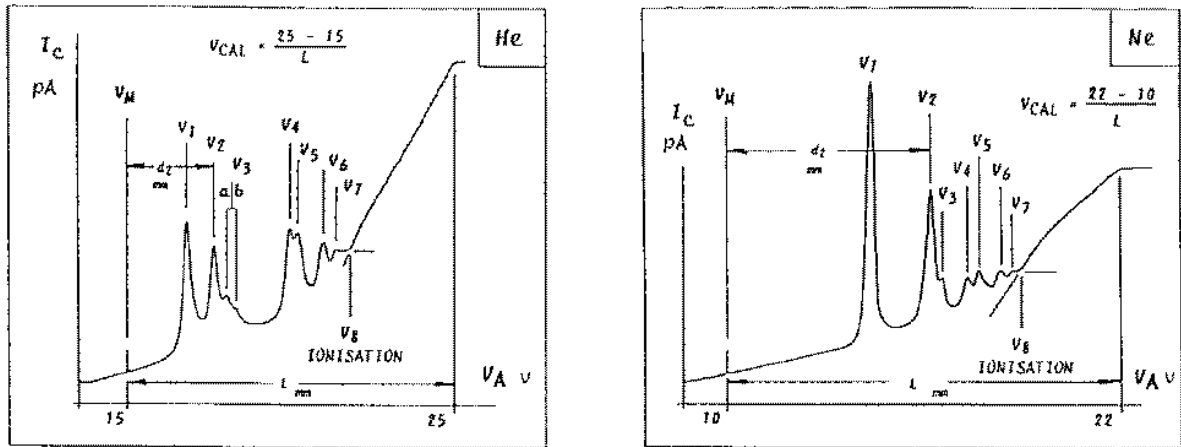


Figure 5.5: Scan of the lower critical region.

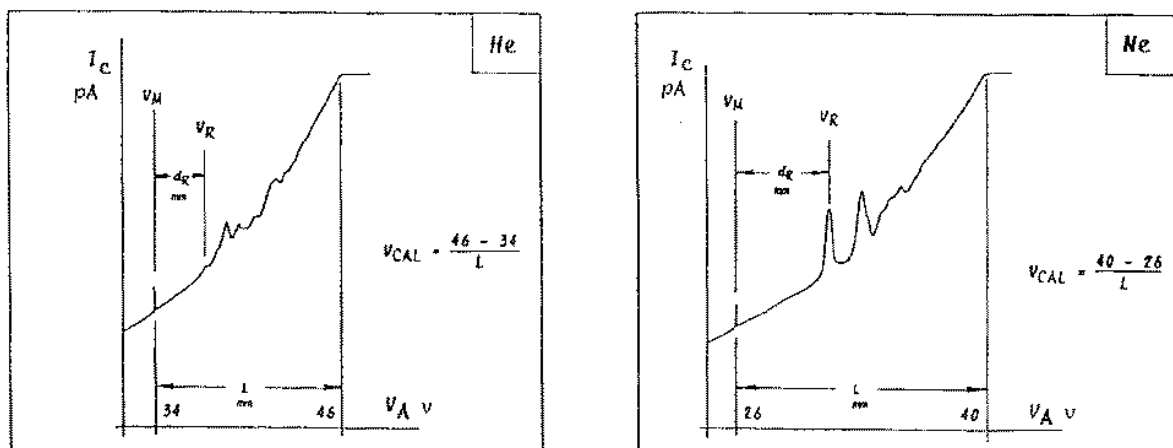


Figure 5.6: Scan of the upper critical region.

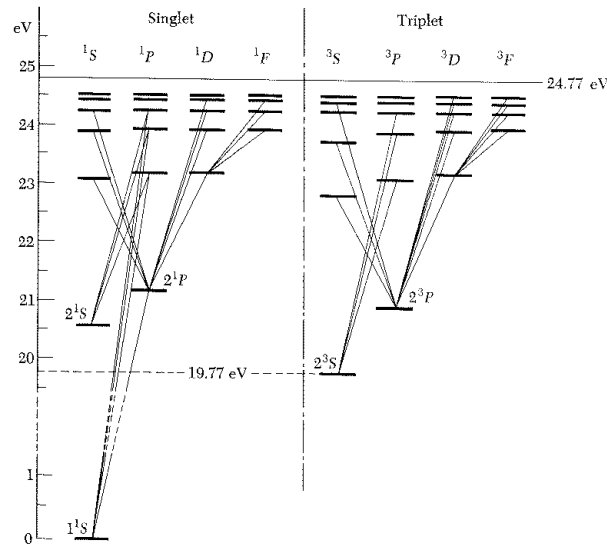
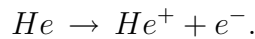


Figure 5.7: Energy levels and electric dipole transitions for the neutral helium atom. Note the separation between the singlet and triplet systems of levels. These systems arise from quantum mechanics.

The atom, with the loss of the negatively charged electron loses its neutral condition and becomes a positive ion. For example, in the case of helium



The accelerating potential difference required to create a positive ion is called the **ionization potential**, V_i

$$V_i = V_{A\infty} + V_O \quad \text{volts} \quad (5.3)$$

The potential difference required to accelerate an electron to create an excited atom is called an **excitation potential**, $V_{e'}$

$$V_{e'} = V_{A'} + V_O \quad \text{volts} \quad (5.4)$$

These excitation potentials are collectively known as the critical potentials (Fig. 5.8).

The experimental scans obtained above show that ionization occurs at V_8 , just after the lower critical region peaks. The upper critical region must therefore represent a repeat excitation process. An electron with energy of V_R has the required energy to excite an atom to the state of V_1 and sufficient residual energy to excite yet another atom to the same state. The upper pattern thus represents a progressive overlay of excitation processes exactly the same as the lower region but caused by electrons 'starting' from V_1, V_2 , etc.

From this, it is clear that the minimum energy required to excite an electron to the first excitation potential, V_{e1} , must be the difference in energy between the peaks V_R and V_1 . Thus

$$V_{e1} = V_R - V_1$$

Experiment 5. The Franck-Hertz Experiment (Critical Potentials)

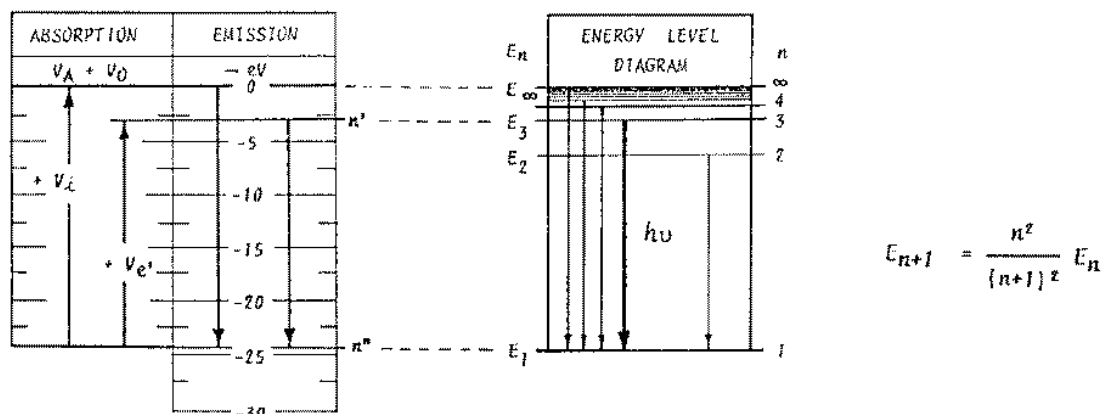


Figure 5.8: Schematic representation of energy levels

But, from Eq. 5.4,

$$V_{e1} = V_1 + V_0$$

therefore

$$V_0 = V_R - 2V_1$$

Accurate values for the other excitation potentials and that of ionization can now be calculated using Eqns. 5.4 and 5.3, respectively. For convenience you should save your data to a file for importing and analysis with a package such as Mathcad or Excel.

Energy levels

Evaluate the allowed energy levels E_n (i.e. $V_e - V_i$, see Fig. 5.8) and form a table such as Table 5.2.

Bohr's model predicts that for an atom with nuclear charge Z , the energy of the electron in the n^{th} level shell is given by

$$E_n = \frac{-13.6 \cdot Z^2}{n^2}$$

where E_n is measured in eV.

Use this equation to calculate a set of predicted critical potentials for Helium or Neon, depending on your apparatus, for $n = 1$ to 10. Identify, if possible, each of your experimental critical potentials, with a principal quantum number, n .

Note: The Bohr model was most successful in the case of the simplest element, Hydrogen.

Questions

1. Do your values of the critical potentials correspond to the values predicted by the Bohr model? Explain.

Table 5.2: The derivation of energy levels.

Feature	0	1	2	3		4	5	6	7
				a	b				
V_e	0								
E_n ($V_e - V_i$)									
n	1								

Reference

'Introduction to Modern Physics', Richtmyer, Kennard and Cooper, for an advanced discussion of energy levels in atoms and the spectrum of helium.

WWW :

- Atomic Theory - http://www.visionlearning.com/library/module_viewer.php?mid=51
- Beautiful animations of atomic orbitals - <http://daugerresearch.com/orbitals>
- Ion propulsion - <http://nmp.jpl.nasa.gov/ds1/tech/ionpropfaq.html>