HERTZ CRITICAL POTENTIALS TUBE 2533

THE HERTZ CRITICAL POTENTIALS TUBE, TEL.2533 comprises a 'cathode ray gun' which projects a divergent beam of electrons into a clear glass bulb which contains gas at low pressure; the gas in 2533/02 is **Helium** and in 2533/10 is **Neon.** Located inside the bulb is a wire ring collector electrode so positioned that it cannot receive electrons directly from the source of the beam ; the ring is connected to a screened lead terminated with a BNC plug . The source of the beam is a tungsten 'hairpin' filament connected to Pins 3 and 4 and housed within a cathode can which is connected to Pin 5 . The anode cylinder of the 'gun' has an external connection at Pin 1 . The inside surface of the glass bulb is coated with a transparent conducting layer ; this coating is insulated from the wire ring but connected internally to the anode cylinder.

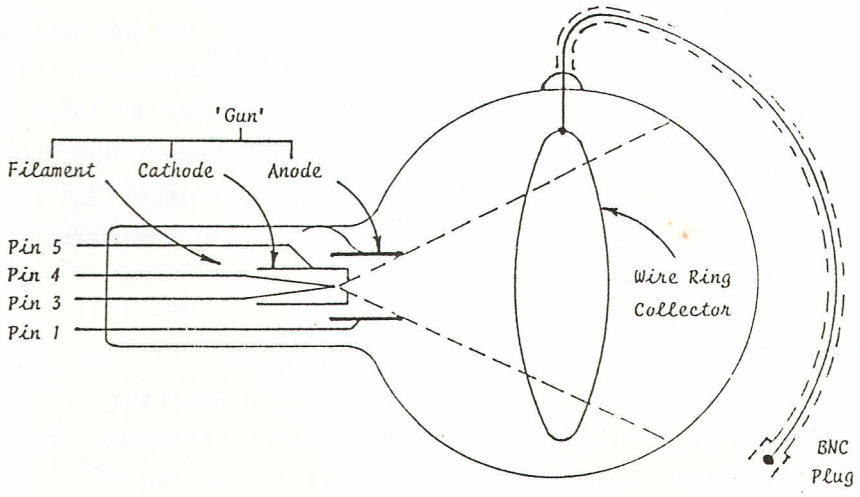


FIGURE 01 : SCHEMATIC OF THE HERTZ CRITICAL POTENTIALS TUBE , TEL.2533

Specification:

FILAMENT VOLTAGE	(V_F)	...	3.0 V dc max.
ANODE VOLTAGE	(V_A)	...	0 - 50 V dc (60 V max)
ANODE CURRENT	(I_A)	...	10 mA max.
COLLECTOR VOLTAGE	(V_C)	...	$\pm$ 1.5 V dc, dry cell battery, type AA (HP7).
COLLECTOR CURRENT	(I_C)	...	0 to $\pm$ 200 picoamps.

The tube is mounted in the **UNIVERSAL STAND, TEL.2501.**

Recommended Experiments:

Experiments with the **DEMOUNTABLE DISCHARGE TUBE, TEL.2530** and the **GAS FILLED PLANAR TRIODES, TEL.2532/02 and TEL.2532/10** demonstrate ionisation of gaseous atoms and molecules resulting from the passage of energetic electrons; the electrons are emitted from both hot and cold cathodes.

In each case a luminous discharge is produced which, when viewed with **SPECTROSCOPE, TEL.2529,** reveals a spectrum which implies the emission of very discrete electromagnetic radiation following collisions between electrons and atoms; in particular the Gas Triode Experiment B.06 with the anode as a retarding plate demonstrates the reduction of the electron population just prior to the production of positive ions.

CHARACTERISTIC LINE SPECTRA.

Identical experiments with Helium and Neon gas emphasise the differing and characteristic nature of line spectra.

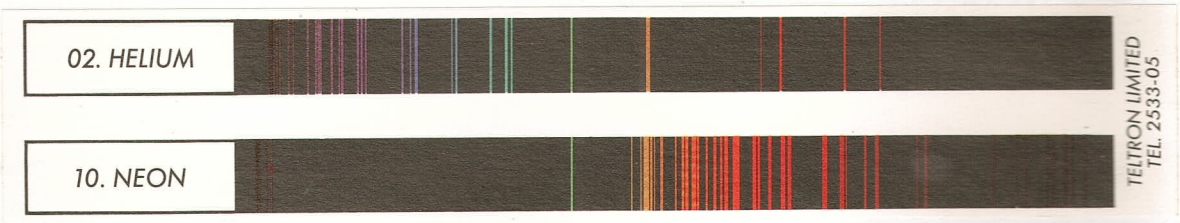


FIGURE 02 : OPTICAL SPECTRA OF HELIUM AND NEON

In the late 1880's optical experiments, in particular with Hydrogen, had identified discrete series of lines, catalogued as **sharp** S , **principal** P , **diffuse** D and fine F ; now defined as the **azimuthal** quantum **number** ℓ, these are equivalent to integers $0, 1, 2$ *and* 3 respectively.

Extensive analysis led to the empirical development of the Rydberg formula to account for the characteristic line spectra, the frequency υ of the different lines being inversely proportional to n^2 where n equals an integer $0, 1, 2 \ldots \infty$.

In modern terminology n is the **principal quantum number** , and ℓ is $n-1$.

Much frustration was experienced at the time brought about by the dilemma that the formula defied all attempts at derivation employing the established newtonian techniques.

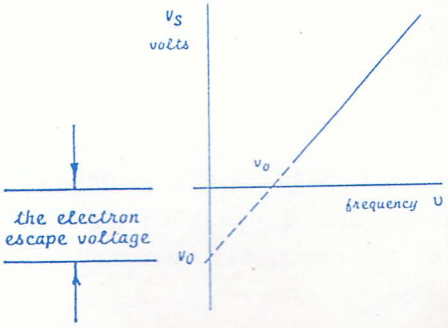
PLANCK, EINSTEIN AND NIELS BOHR.

In 1900 **Max Planck** published a paper on black body radiation; he proposed that light was emitted as particle-like units which were named **quanta** and that these packets each contained an amount of kinetic energy E where

$$E = h\upsilon \qquad (eV)$$

where h is a universal constant, Plancks constant and υ is the frequency of radiation (See Note 1.0 , page 12).

In 1906 **Albert Einstein** inverted this theory by proposing a linear relationship between the frequency of incident radiation in the photo-electric process and the kinetic energy of the resultant photo-electron.



$$V_S + V_0 = h\upsilon \qquad (eV)$$

FIGURE 03 : PHOTO-ELECTRON STOPPING POTENTIAL

V_S in terms of electron-volts is the energy required to stop the departure of an electron at the surface of a material exposed to incident radiation of energy $h\upsilon$ and where V_0 is the energy required to extract the electron from within the material to that surface (See Note 2.0 , page 12).

Conversely, by Einstein's theory of the equivalence of absorption and emission, in the absence of radiation a surface electron must be accelerated to the potential V_S to acquire energy equal to $h\upsilon$; if accelerated by an electron gun, where the anode is at potential V_A then $V_A = V_S$ and hence

$$V_A + V_0 = h\upsilon \qquad (eV) \qquad 10.02$$

In 1913 **Niels Bohr** published two statements which introduced a revolutionary quantised arrangement by which an atom organises its ability to absorb and emit energy through the medium of electrons orbiting circles centred on the nucleus.

In the first statement Bohr postulated that a planetary electron can only rotate in orbits where its angular momentum is $n \times h/2\pi$ where n is the principal quantum number, an integer.

In the second statement Bohr postulated that no atom radiates energy so long as all of its orbital electrons remain in the permitted state $-E_n$, the electron being negatively charged possesses negative potential energy; radiation occurs only when an electron makes a **quantum jump** from a higher level to a lower and more negative one, the energy of the quantum of radiation $h\upsilon$ being equal to the difference in energy of the states ΔE_n.

According to the Rydberg formula $h\upsilon$ is proportional to $1/n^2$ and so an electron orbiting at a higher level n' (say 3) possesses more energy than that at a lower level n'' (say 1) hence

$$h\upsilon = \Delta E_n = E_{n'} - E_{n''} \qquad 10.03$$

GASEOUS COLLISIONS.

Electrons passing through a gas undergo two types of collision with atoms or molecules, elastic and in-elastic.

In elastic collisions the energy of motion is conserved; the kinetic energy of the incident electron equates to the sum of the motions of the particles after collision.

In in-elastic collisions the energy of motion is not conserved; some of the kinetic energy of the incident electron is transferred to the atom to excite a bound electron from the normal lower orbit n'' to one of the permitted upper orbits n' ; the n' level having a greater orbit than n'' is further removed from the nucleus.

Niels Bohr proposed that this 'excited' atom then returns to the 'ground state' as rapidly as possible, estimated to be of the order of 10^{-8} seconds; in so doing, the atom will emit energy ΔE_n.

Electrons from an electron gun can be made to acquire the exact amount of energy to excite an atom to different levels by the correct adjustment of the accelerating potential V_A and from equations 10.02 and 10.03

$$E_{n'} - E_{n''} = V_A + V_0 \qquad 10.04$$

This is the basic equation for the ensuing experiments.

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

$$E_\infty - E_{n''} = V_{A\infty} + V_0 \qquad \text{and} \qquad E_\infty \text{ is zero by convention.}$$

The atom, with the loss of the negatively charged electron loses it's neutral condition and becomes a **Positive Ion.**

$$He \rightarrow He^+ + e \qquad \text{where } He^+ \text{ is in its ground state.}$$

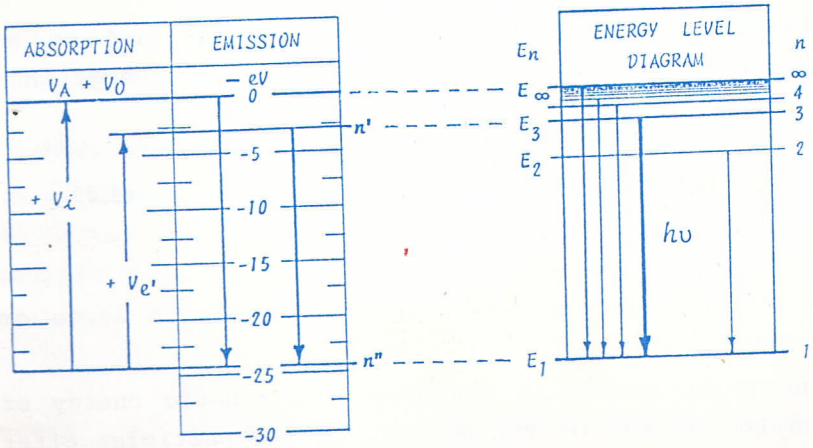
The accelerating p.d. required to create a positive ion is called an **Ionisation Potential, V_i**

$$V_i = V_{A\infty} + V_0 \quad \text{volts} \qquad 10.05$$

The potential difference required to accelerate an electron to create an excited atom is called an **Excitation Potential, V_e**

$$V_{e'} = V_{A'} + V_0 \quad \text{volts} \qquad 10.06$$

These are collectively known as CRITICAL POTENTIALS.



$$E_{n+1} = \frac{n^2}{(n+1)^2} E_n \qquad 10.07$$

FIGURE 04 : DIAGRAMMATICAL REPRESENTATION OF ENERGY LEVELS.

HISTORICAL EXPERIMENTS

Theoreticaly an electron with energy corresponding exactly to an Excitation Potential will, after collision with a neutral atom have no residual energy.

Similarly if an incident electron has energy corresponding exactly to the Ionisation Potential , the liberated electron will also have no residual energy.

All the historical electrical experiments attempt to detect "de-energised" electrons as verification of the Bohr proposals.

J.Franck and G.Hertz experimented with mercury vapour and published their results in 1914. Two other collaborative pairs published papers in 1917; **Davis and Goucher** with gas filled apparatus and **Tate and Foote** with sodium vapour.

All these early experiments were disappointing in that they did not yield any appreciable fine structure; this was finally achieved by **G.Hertz** again in 1923, this time working with his son.

The Teltron tube is a variation of this experiment.

THE HERTZ CRITICAL POTENTIALS EXPERIMENT:

There are two parts to the Hertz experiment; in the first part all the Critical Potentials are measured as current peaks; in the second part the Ionisation Potential V_i is identified, the remaining features being discrete Excitation Potentials V_{e1}, V_{e2} etc.

Electrons from a simple 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 experimental region of the TEL.2533 tube. In this region those which experience only elastic collisions traverse the bulb to impact with the conductive coating and return to the anode and so contribute to I_A.

Electrons which undergo "de-energising" in-elastic collisions become attracted to the small positive potential $+V_C$ of the wire ring collector to be measured as I_C picoamps (see Note 3.0 page 12).

When the potential of the collector is reversed to $-V_C$ any positive ions in the vicinity become attracted and collected as $-I_C$ also in picoamps.

EXPERIMENT B.10 - THE EXCITATION OF GASEOUS ATOMS.

TIME - 40 mins	V_F - TEL.2800	V_A - TEL.2801	I_C - TEL.2808	V_C - BATTERY UNIT WITH TUBE.

10.01 Connect up the filament supply immediately to allow the electrode system to achieve thermal stability (see para **10.06** below). Then connect the **TEL.2533** Tube into the circuit of **FIGURE 05.**

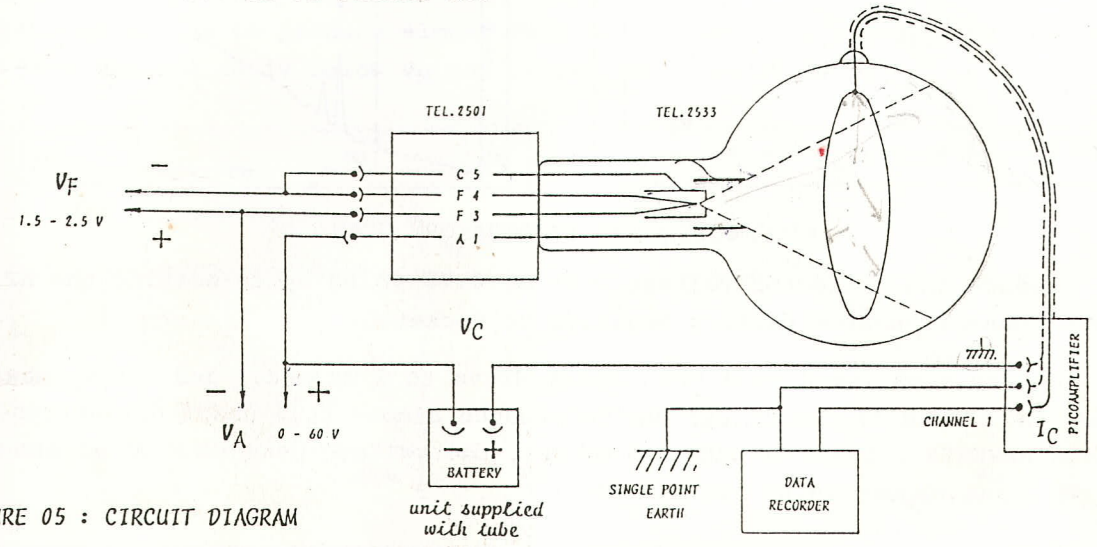


FIGURE 05 : CIRCUIT DIAGRAM

It is recommended that the **Teltron Mechanical Drive Data Acquisition System** is used in conjunction with **Ramp 60** of **TEL.2801** to provide the anode voltage V_A, and that the I_C / V_A characteristic is recorded on a suitable Chart Recorder or Data Logger (see Note 4.0 page 12).

Attach **AUTOSCAN, TEL.2003** to **HIGHVOLT DIGIRAMP, TEL.2801.**

Connect the Chart Recorder to the **PICOAMPLIFIER, TEL.2808** Channel 1 output $\pm$ 1V such that I_C is registered as increasing from zero in the conventional **X / Y** manner; this may also require a full width shift of chart zero setting.

10.02 Ensure **SCAN CONSOLE, TEL.2030** is at full **REVERSE** travel to minimum; set **PPS** to **12**, Travel to **FORWARD** and Event to **STOP.**

10.03 Set Channel 1 of **PICOAMPLIFIER, TEL.2808** to 10^{-12} range.

10.04 Select chart speed (or time-base) of **5mm/sec** .

10.05 With **RAMP 60** disabled (LED off) adjust V_A to **50V** .

10.06 Enable **RAMP 60** (LED on) and adjust V_F in the region **1.6 to 2.6** volts using the fine control on the top surface of **LOVOLT DIGIRAMP, TEL.2800** to produce almost full chart deflection; if another power supply is used in place of the **TEL.2800** instrument it is recommended that the fine control required is achieved by using the 10-turn helical potentiometer incorporated in the **RAMPGEN TEL.2023** module. It may be necessary to alternately adjust the minimum and maximum scan settings and this is conveniently achieved by using the **RAMP 60** enable control to rapidly switch from the minimum to the chosen full scale deflection.

AN EXPLORATORY SCAN :

10.07 Enable **Ramp 60** (LED on), start chart and set scan to **FORWARD** and **RUN**.

10.08 Observe the incremental display of V_A and rapidly register the 'MARK' voltage V_M as shown on the respective **FIGURE** (in this case 10V from **FIGURE 06**).

10.09 When the scan is complete stop the chart drive and press event **STOP**.

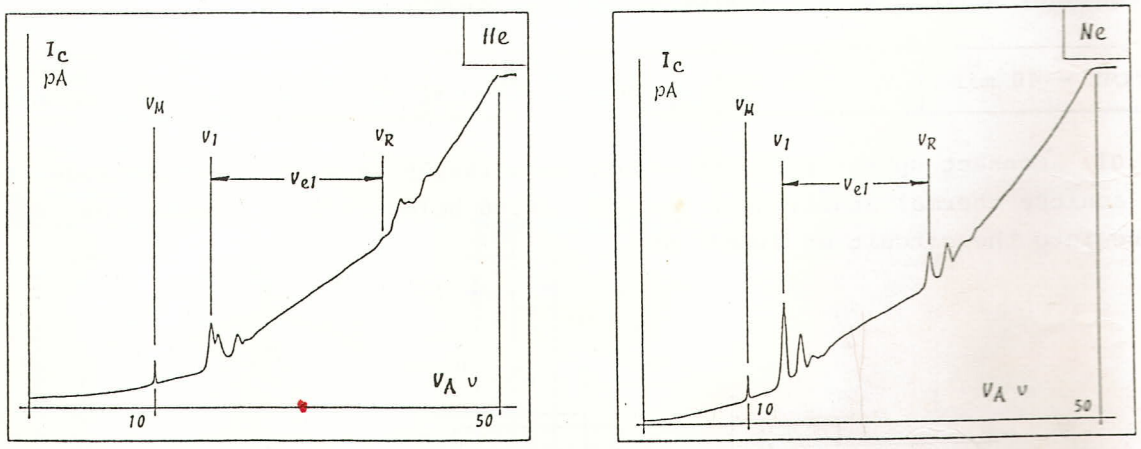


FIGURE 06 : THE EXPLORATORY SCAN :

10.10 Reduce the collector voltage + V_C to **0.75** volts by relocating the HT 4mm positive connection from Battery Negative to **Socket B**.

10.11 Reduce scan speed to **3 PPS** , chart drive to **2 mm/sec.**, and set V_A maximum as shown in **FIGURE 07** and adjust V_F to produce almost full chart deflection. Set travel to **REVERSE** , event to **RUN** and reverse the voltage scan to **STOP** at about 1V below V_M and repeat **10.07** to **10.09** .

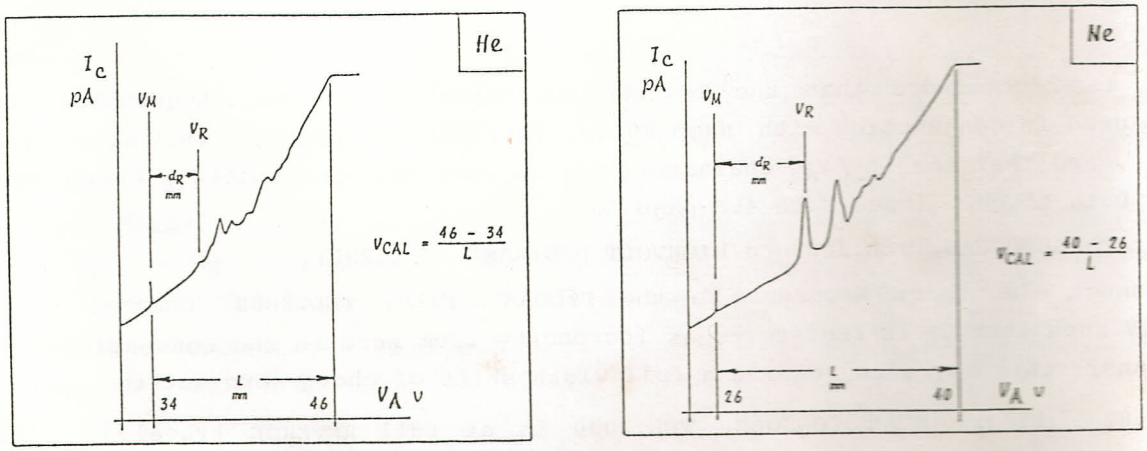


FIGURE 07: SCAN OF UPPER CRITICAL REGION:

10.12 Set V_A maximum as shown in FIGURE 08 and adjust V_F to produce almost full chart deflection; set scan minimum to 1V below V_M and repeat 10.07 to 10.09.

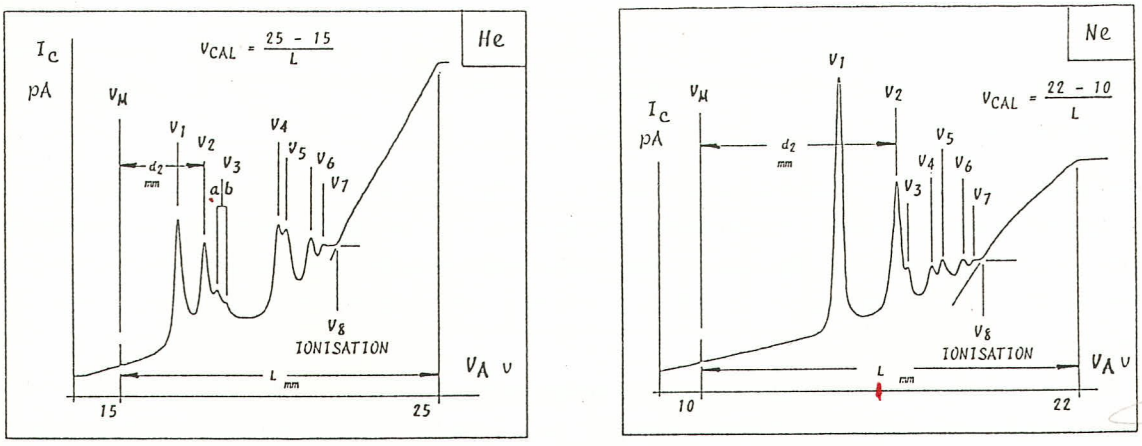


FIGURE 08: THE LOWER CRITICAL REGION.

THE IDENTIFICATION OF IONISATION:

10.13 Reverse the 1.5V Battery in it's holder.

10.14 Maintain the connections to the Battery Board and the setting of V_A max.

10.15 The positive ion current should record in the opposite polarity to the electron current and so the chart recorder zero should be shifted to about three-quarter full-scale.

10.16 Adjust V_F to produce almost full scale (negative going) chart deflection; set scan minimum to 1V below V_M and repeat 10.07 to 10.09.

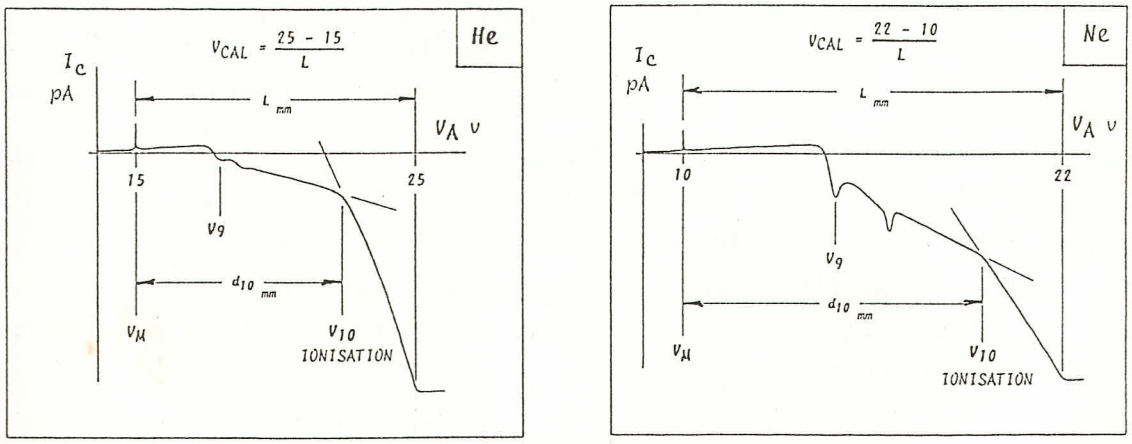


FIGURE 09: THE IDENTIFICATION OF IONISATION.

10.17 Extrapolate the voltage at ionisation, V_8 from the intersection of the tangents to the curves of FIGURE 08 or V_{10} from FIGURE 09 , whichever displays the more clearly defined change of gradient.

METASTABLE STATES:

The onset of ionisation at first peak, V_9 (which is V_1 with a different calibration factor) infers that the excited electron is not relaxing rapidly back to the ground state but remains long enough at E_2 to receive yet another

collision with sufficient energy to raise the already excited E_2 electron to ionisation; the atoms of some elements can remain in this METASTABLE STATE for times varying from seconds to even days; the effect is most apparent at the first two excitation potentials and the shape of the following curves of FIGURE 09 is probably due to similar effects occurring during 'cascading' of an elevated electron to the ground state.

These scans show that Ionisation occurs at V_8 just after the Lower Region peaks; the Upper 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.; the Pattern therefore does not match the Lower one especially for the first few features. The electron intensity of the two 'metastable states' V_1 and V_2 is exaggerated due to the liberation of electrons following 'premature' ionisation and the intensity of the first three peaks of the Upper Region conforms more to theoretical evaluation.

It is however clear that peak V_R is not compromised by the progressive overlay and 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 $$V_{e1} = V_R - V_1 = V_1 + V_0$$ from equation 10.06

and $$V_0 = V_R - 2V_1$$ 10.08

Accurate values for the other excitation potentials and that of ionisation can now be calculated. Note that for Helium there is the witness of another feature, *3b* just after that of *3a* and this does not seem to be present in the Neon scan.

SCAN CALIBRATION:

10.18 Measure the distances from the **MARK** voltages, V_M of all the scans to the maximum scan settings of V_A ; the voltage difference divided by the distance L mm will yield calibration factors V_{CAL} in volts/mm for each scan.

10.19 Enter the **MARK TO PEAK** dimensions d mm of all the features 1 to 8, R and 10 in **TABLE 01** below and using the recorded values for V_{CAL} calculate the value for V_0 and hence for $V_{e'}$ and V_i .

FEATURE		1	2	3 a	3 b	4	5	6	7	8	R	10
d	mm											
X V_{CAL}	v											
+ $V_M = V_{A'}$	v	>									<	
+ $V_0 = V_{e'}$	v									+		+

TABLE 01 : THE EVALUATION OF THE CRITICAL POTENTIALS.

> is V_1
< is V_R
+ is V_i

10.20 Evaluate **the permitted atomic states** E_n (*i.e.* $V_e - V_i$) and see if it is possible , using equation 10.07 to allocate the **principal** n and the azimuthal quantum numbers S, P, D, F with $\ell \leqq (n-1)$.

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

TABLE 02 : THE DERIVATION OF ENERGY LEVELS.

Note that the ratios of **Excitation Potential** do not exactly equate to $n^2 / (n+1)^2$ For Feature 1 the value for n must be **2** .

It becomes apparent by trial and error that for the second and third peaks n is 2 rather than 3 ; similarly for the fourth/fifth pair n is 3 rather than 4 .

For $n = 1$ the azimuthal quantum number ℓ must be 0 (i.e. S).

For $n = 2$ the two possibilities for ℓ are **0** and **1** but it is notable that the scan indicates at least three levels; the lowest must be **0** but the upper levels may be **0** or **1** or both if their seperation is beyond the resolution of this experimental system.

At level $n = 3$ the three possibilities for ℓ are **0**, **1** and **2** ; here the scan has yielded only two levels and it is reasonable to assume that the third level is not resolved, as must be the case with levels $n = 4, 5$ etc.

THE EQUIVALENT VISIBLE SPECTRUM:

10.21 Enter the values of E_n from peaks 1 to 7 into **TABLE 03** and calculate the energy in electron volts of all the possible transitions from each level to each of the lower levels.

$$h\upsilon = \Delta E_n = E_{n'} - E_{n''}$$

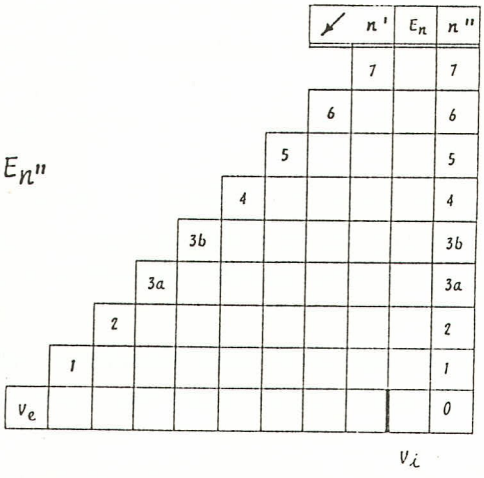


TABLE 03 : THE POSSIBLE TRANSITIONS.

The visible spectrum is in the region 1.50 to 3.25 eV ; of these 36 possible transitions only about one third are in the visible region.

10.22 Place a sheet of tracing paper over FIGURE 10 below and draw vertical lines corresponding to the transitions calculated above in Table 03 .

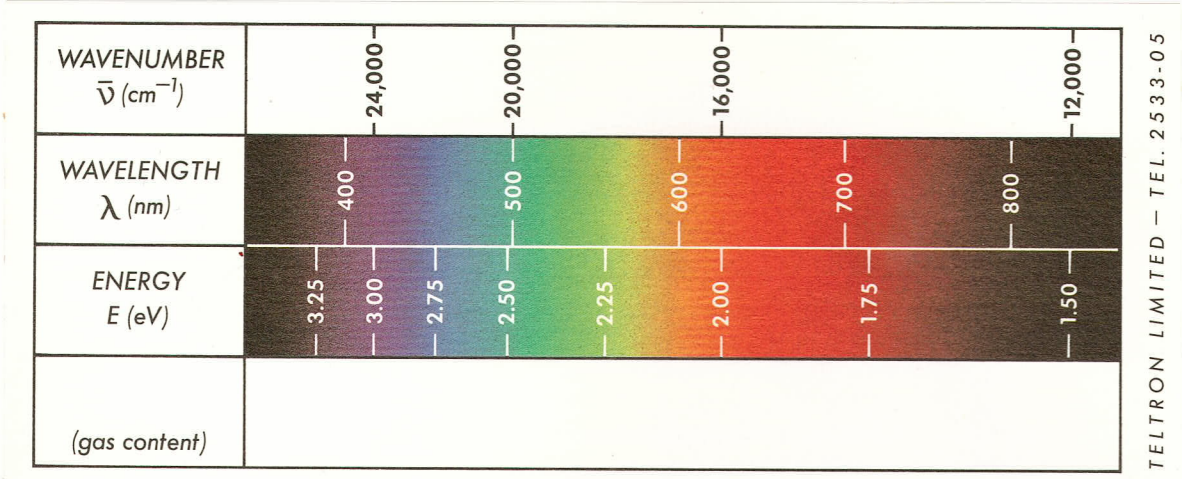


FIGURE 10 : A CONSTRUCTED SPECTRUM.

(See Note 5.0 , page 12).

10.23 Compare the resultant line spectrum with FIGURE 02 . Verify the existance of the *3b* level for Helium by locating some visible lines due to the possible transitions from the four upper levels.

EXPERIMENTAL CONFIRMATION :

10.24 Use crayons to colour the lines of the constructed spectrum to match those of FIGURE 02 .

10.25 Disconnect the battery unit and remove the battery ; connect the positive of the 300V output of TEL.2801 to Socket D on the battery unit and the negative of the output to the battery positive Socket and also to Earth. Increase the voltage until the discharge strikes in the COLD CATHODE CAPSULE (it may be necessary to series connect the 60V output to achieve a range extended to 360V).

CAUTION - THE CAPSULES BECOME VERY HOT WITH PROLONGED USE.

10.26 Using the SPECTROSCOPE, TEL.2529 observe the spectrum.

10.27 Compare the image with the coloured constructed spectrum. Reduce the voltage of the Neon discharge to minimise the intensity of the complex spectrum for the purpose of comparison.

CONCLUSION :

These experiments are intended to create an easily imaginable model of the Bohr concept of an atom having electrons occupying quantised orbits and to be a convincing introduction to the modern interpretation of the Quantum Theory and associated wave mechanics.

The Bohr model for Hydrogen with one electron orbiting in certain permissible circles has the energy condition of that one electron well defined by one quantum number , n .

But it is evident from 10.20 that one quantum number is not sufficient to specify the energy condition of electrons orbiting the nucleus of a multi-electron atom. In 1915 an extension to the Bohr circular orbit theory was independently proposed by A. Summerfeld and C.Wilson to provide for elliptical orbits with the nucleus as a focus and so introducing the second quantum number ℓ.

SHELL	K	L		M		
n	1	2		3		
ℓ	0	0	1	0	1	2
01. H	1					
02. He	2					
03. Li	2	1				
10. Ne	2	2	6			
11. Na	2	2	6	1		

TABLE 04 : CONFIGURATIONS WITH TWO QUANTUM NUMBERS.

Neon with 10 electrons has the first 2 shells, K (2 electrons) and L (2 + 6 electrons in 2 subshells) complete . The first excitation is therefore to $n = 3$ with three possible values for ℓ ; the subsequent complexity of the possible electron configurations and atomic transitions is not addressed in this student enquiry.

The introduction of elliptical orbits still does not clarify the spread of levels calculated or the observed additional lines in the visible spectrum or the sub-divisions revealed by the influence of magnetic and electric fields (P.Zeeman, 1896 and J.Stark, 1913 respectively).

This infers that two quantum numbers is also not sufficient to specify the energy condition of an electron orbiting the nucleus of an atom; this deficiency leads to the development of more sophisticated theories to quantify spin and magnetic quantum numbers, s and m .

A comprehensive knowledge of Ionisation Potentials is essential to the compounding of most chemical elements. The large values for the Ionisation Potential of Helium and Neon are typical of elements with a complete outer shell; elements such as the alkali metals with one valence electron all exhibit relatively small values and the Periodicity of the Elements is well illustrated by a study of Ionisation Potentials.

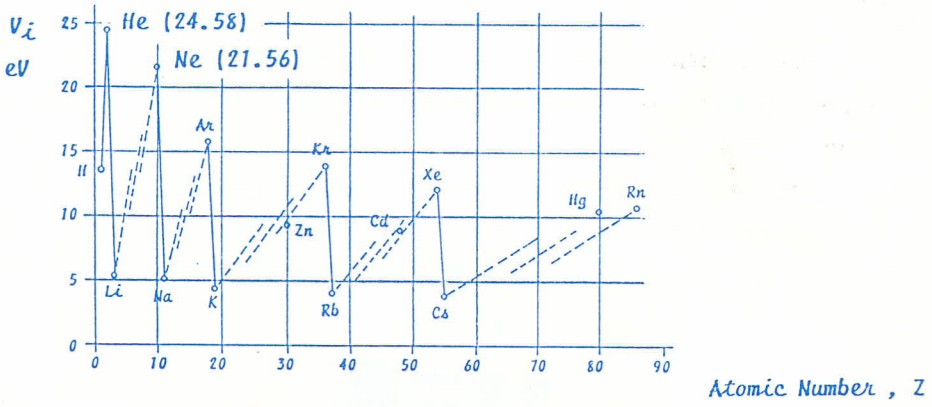


FIGURE 11 : THE PERIODICITY OF THE ELEMENTS.

QUALITY OF RESULTS :

This series of experiments yields results which are accurate to within ± 3.0 percent and the resolution appears to be about 0.25 volts ; this is the voltage evaluated in Table 03 for the transition feature $5 \rightarrow 4$. The width of separation of the spectroscopic features $5 \rightarrow 3a$ and $4 \rightarrow 3a$, also about 0.25 volts illustrates the superior resolution of diffraction analytical techniques.

NOTES :

1.0 UNITS OF MEASUREMENT :

Planck's Constant h has an accepted value of 6.626×10^{-34} joules.sec .

When studying the energy of electrons the preferred unit is the **Electron Volt.** Energies in joules are converted to electron volts by dividing by the factor

$$1.602 \times 10^{-19} \quad \text{joules per electron volt.}$$

Hence $$E = \frac{6.626 \times 10^{-34}}{1.602 \times 10^{-19}} \cdot \nu = 4.136 \times 10^{-15} \cdot \nu \quad \text{(sec.eV)}$$

According to Maxwell's classical theory $\nu = c / \lambda$ where c is the speed of light 2.998×10^{8} m.sec^{-1} and λ the electromagnetic **Wavelength** and by juxtaposition

$$\lambda = \frac{1240}{E} \quad \text{nm.}$$

When the wavelength becomes large the unit often preferred is the **Wavenumber,** $\bar{\nu}$ where $\bar{\nu} = 1 / \lambda$ cm^{-1} and so electromagnetic energy can also be expressed

$$\bar{\nu} = \frac{E}{1240} \times 10^{7} \quad \text{cm}^{-1} .$$

The spectroscopic image using TEL.2529 is linear with respect to wavelength and consequently **FIGURES 02** and **10** are based on wavelength linearity.

2.0 In these experiments V_0 is a combination of emission energy (variously referred to as ionisation energy or thermionic work function), filament voltage distribution and contact potential difference resulting from electrodes of dissimilar metals. After many subtle experiments **R.A.Millikan** showed that, for a metal, photo-electric and thermionic emission involves electrons which are already in the free state inside the metallic surface and no energy is used in extracting electrons from the constituent atoms of the emitting metal.

3.0 The collector currents are very small, typically around 100 pA and any movement close to the glass bulb during scanning is liable to seriously distort the results.

4.0 It is not easy to co-ordinate the start of a scan with any precision and this series of experiments makes use of a **Mark** facility incorporated into most popular chart recorders and data loggers; the **Mark** can be accurately registered once a scan has commenced.

5.0 Copies of **FIGURE 10 , A Constructed Spectrum** are available in this adhesive form , boxed in quantities of 16 , as Teltron Catalogue Number TEL.2533/05. The box also contains 16 copies of Figure 02, Optical Spectra of Helium and Neon.