FRANCK HERTZ EXPERIMENT SET - xenon gas

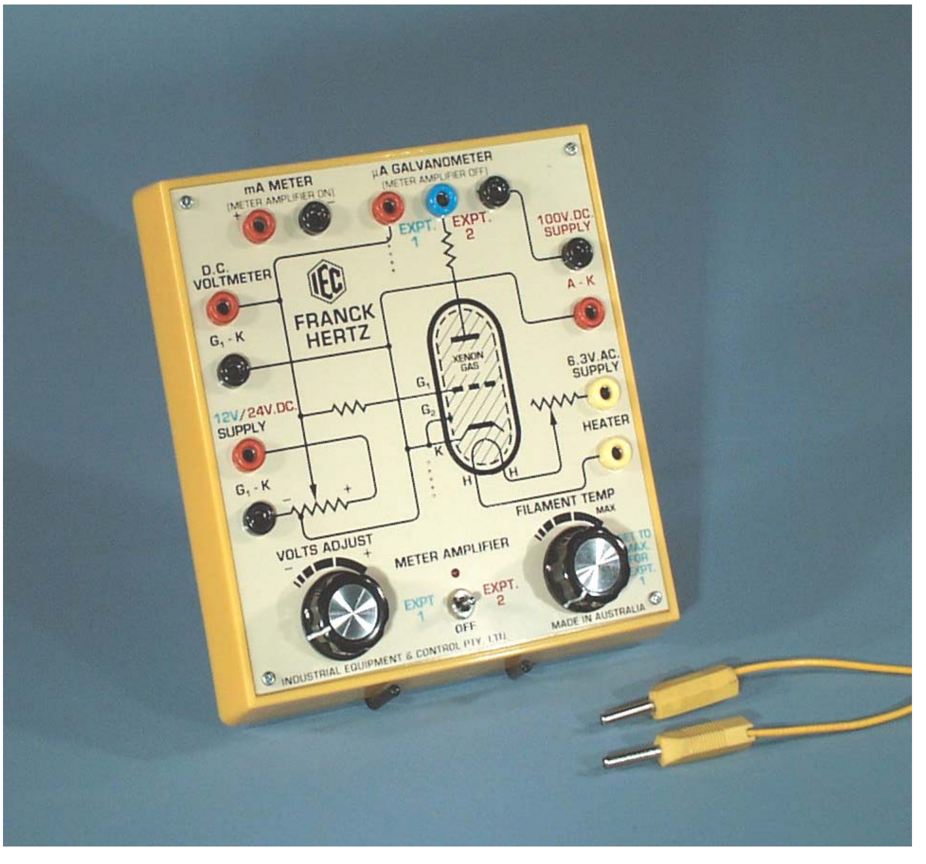
Cat: AP1870-001   Using Xenon gas

THE 'FRANCK HERTZ' EXPERIMENTS:

#1: The First Excitation Potential of Xenon gas

#2 The Ionization Potential of Xenon gas

AP1870-001



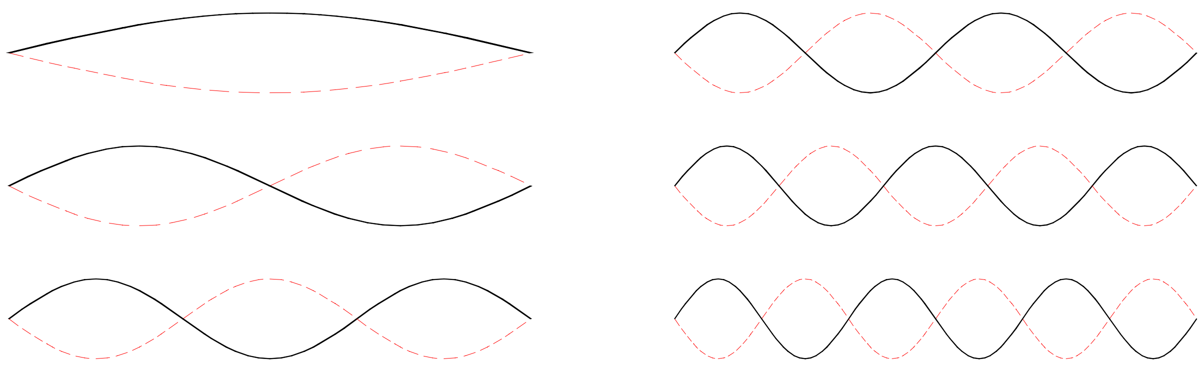
Physical size: 160x170x45mm LxWxH   Weight: 0.34kg.

THE THEORY:

Rutherford's Theory of the atom structure was that atoms were like small spheres with spaces between them. Bohr's Theory demands a modification to Rutherford's theory. Bohr states that the atom consists of a relatively massive nucleus surrounded by orbiting electrons in various configurations and with various energy levels (or shells).

We know that if we fix the ends of a vibrating string or wire or fix the length of a resonating column of air or make waves in water in a restricted space, the result is the production of `standing waves'. We assume therefore that, under physically limiting conditions, there are only certain frequencies of vibration that are possible.

For example, we can produce only these (and similar) patterns on a vibrating spring.



The wave length in each case above is always related to the length of the spring by:

$l = n \lambda / 2$ where l = length of spring n = number of nodes λ = wavelength

Also, the velocity of propagation is fixed by the nature of the spring because of its density and tension. The acceptance of the previous statements forces the acceptance that only certain natural frequencies are possible, that is, certain masses vibrate only at certain frequencies.

This statement then implies that only certain ENERGY LEVELS are possible. It is believed that, similar to above, the orbiting electrons in the structure of the atom are limited by their orbits to certain frequencies and energy levels. Also, if they are bombarded by projectile electrons (like bullets), or energised in any other way (eg. X-ray bombardment), the orbital electrons can accept only sufficient energy to raise them to exactly the next or some higher energy level. If the energy supplied by the external energy source is not sufficient to raise the orbiting electron to a higher level, then no energy at all is absorbed in the collision.

This type of collision is called an 'elastic collision', since MOMENTUM and ENERGY are both conserved.

The aim of this experiment is to determine if there are such discrete ENERGY LEVELS and also to find what energy of bombardment will lift an orbiting XENON electron to a higher level. This means to its **'First Excitation Level'.**

To do this we need:

- A source of electrons to use as bombarding bullets.
- Some means of accelerating these bullets.
- Some way of knowing what energy level these bullets have reached before they hit the XENON atoms.
- Some means of knowing if these bullets have in fact collided with XENON atoms.
- Some means of finding out what energy the bullets have lost.
- A near vacuum with some XENON atoms in it so that the projectile electrons do not collide with anything else.

All these facilities are provided in a small glass tube as big as your finger.

It is called a **'Thyratron'** electron valve and the circuit required is provided by one section of the IEC **Franck Hertz** circuit board.

GENERAL BRIEF DESCRIPTION OF OPERATION OF AN ELECTRON VALVE:

The glass valve is visible through the transparent base cover of the instrument. Observe the valve and read the following description.

In the centre of the valve's glass envelope a Heater is mounted inside a small tube of special material. This tube is called the Cathode and it is heated so that it can emit electrons.

A mesh of fine wires surrounds the Cathode and this is called the Control Grid. Outside the Control Grid a metal plate surrounds everything and this is called the Anode or 'Plate'. An electron tube or 'Valve' that has only these three fundamental elements is called a 'Triode'.

The Cathode is the source of electrons which 'boil off' its surface at a rate that depends on the temperature of the Cathode.

By applying a potential to the Grid mesh, the flow of electrons from the Cathode to the Plate can be controlled. This means that the current flow through the Valve from Cathode to Plate (high power) can be controlled by a potential on the Control Grid (very low power).

If the Grid mesh is made negative, the flow of electrons from the Cathode to the Plate is controlled as electrons are repelled from the Grid but some pass between the Grid mesh wires and are attracted to the positive Plate. Therefore some Plate current flows.

If the Grid is made positive, the electrons are attracted to the Grid from the Cathode and are accelerated towards the Grid and the Plate. Some are attracted to the positive Grid mesh thus causing Grid current to flow and most electrons pass through the spaces between the Control Grid mesh and continue to the Plate thus causing a large Plate current to flow.

Therefore it can be seen that the Plate receives any electrons that are emitted from the Cathode and which have sufficient energy to pass through the wires of the Grid mesh. This current flow depends on three factors:

- The temperature of the Cathode.
- The voltage between the Cathode and the Plate.
- The voltage between the Cathode and the Grid.

The above description is true for a 'vacuum valve', but the valve used for the **Franck Hertz** experiment is not a complete vacuum. The glass envelope contains a small quantity of Xenon gas. The electrons passing through the spaces between the Cathode, Grid and Plate collide with Xenon atoms and cause IONIZATION. This means that the Xenon atom carries an electric charge and it is no longer at neutral potential.

Notice that in the **'Thyratron'** valve, there is a second 'Grid' that surrounds everything else. This is not a Control Grid but it behaves as a 'Faraday Screen' around all the other valve components to protect them from any extraneous electric fields.

DESCRIPTION OF THE ‘FRANCK HERTZ’ INSTRUMENT:

The IEC **Franck Hertz** Experiment Board consists of an Electron Valve configured to behave as a miniature laboratory to detect the behaviour of Xenon gas atoms when bombarded with electrons.

The two rotary controls provide the following adjustments:

‘VOLTS ADJUST’ controls the voltage on the Control Grid from slightly negative to the Cathode up to positive to the Cathode. Experiment #1 requires up to 12V.DC. at the Grid and Experiment #2 requires up to 24V.DC. on the Grid.

This Grid voltage controls the flow of electrons from the Cathode to the Anode (or Plate).

‘FILAMENT TEMP’ controls the voltage to the heater which controls the heating of the Cathode and controls the quantity and energy of the electrons 'boiled off' the surface of the Cathode.

The various socket terminals permit the following connections:

- HEATER power source for the heater (typ. 6.3V.AC.)
- 12V/24V.DC. SUPPLY G1-K power source for the Grid (typ. 0-24V.DC.)
- 100V.DC. SUPPLY power source for the Anode (typ. 0-100V.DC.)
- DC VOLTMETER G1-K connection for a Voltmeter to measure voltage set between Cathode and Control Grid.
- uA GALVANOMETER connection for a sensitive Galvanometer to measure very small currents flowing in the anode circuit for either Experiment #1 or Experiment #2. These terminals are used ONLY when the inbuilt DC Amplifier is switched OFF. Very small current to be detected is about 1 or 2 microamps.
- mA METER connection for a normal student milliameter or multimeter if a sensitive Galvanometer is not available. These terminals are active ONLY when the inbuilt DC Amplifier is switched ON.
- METER AMPLIFIER switch to operate the optional inbuilt DC Amplifier in either Experiment #1 or Experiment #2 mode. When selected, the correct connections are automatically made for the Anode circuit and no connections are required at the Anode terminals. A red LED indicates that the Amplifier is switched ON.

NOTE: When the instrument is not in use, ALWAYS turn this amplifier switch OFF to conserve the internal 9V. battery.

THE THEORY OF THE EXPERIMENT:

Experiment #1 'The First Excitation potential of XENON gas'

The filament or HEATER will glow red hot when 6.3volt AC is applied. Electrons are then 'boiled off' from the Cathode 'K'.

The Control Grid 'G1' is made positive so that electrons are drawn from the relatively negative Cathode and accelerated toward the positive Grid. The rate of acceleration towards the positive Grid is dependent on how highly positive the Grid is made - that is, the positive potential difference between the Cathode and the Grid. This voltage is measured by a voltmeter connected to the 'DC.VOLTMETER' socket terminals.

For every volt that we raise the Control Grid above the Cathode potential we impart one Joule (1 Newton Metre of work) to each Coulomb of electric charge that we move across from the Cathode to the Control Grid.

So, it follows that if 1 Coulomb receives 1 Joule from 1 Volt potential difference and further if 1 Coulomb = 6.25×10^{18} elementary charges and 1 electron carries 1 elementary charge, then 1 electron receives: $1 / 6.25 \times 10^{18}$ Joules from a 1 Volt Potential Difference.

So, 1 electron receives 1.6×10^{-19} Joules from 1 Volt P.D. This amount of energy is called an ELECTRON VOLT (eV).

This amount of energy imparted to the electron takes the form of kinetic energy (which we could calculate by using $1/2mv^2$ (if we knew its mass and velocity) and the electrons reach the GRID with this AVERAGE amount of energy. We say average because some of them may have been partly retarded on the way from the Cathode to the Grid by the cloud of electrons around the Cathode. This effect is known as 'Space Charge Limitation'.

Since the Grid is perforated like a gauze, some of the electrons pass through it with just this velocity and its associated kinetic energy. We can detect if any electrons do in fact pass through the Grid and we can detect the quantity by making the Anode (or Plate) positive potential to attract and collect these negatively charged electrons. A sensitive microammeter or galvanometer is connected into the Anode circuit to detect and 'count' them.

If we detect one micro amp, we know we have 10^{-6} of an amp and we know that one Amp is 1 Coulomb of charge per second or 6.25×10^{18} elementary charges (or electrons) per second.

So 1 micro amp = $6.25 \times 10^{18} / 10^{6} = 6.25 \times 10^{12}$ elementary charges / second. That number is 6.25 million million electrons per second.

If these bullet like projectile electrons which have passed through the Control Grid collide with a XENON atom and if they can lose their energy and leave an exited atom in return, then the projectile electrons will not have sufficient energy (velocity) to reach the Anode.

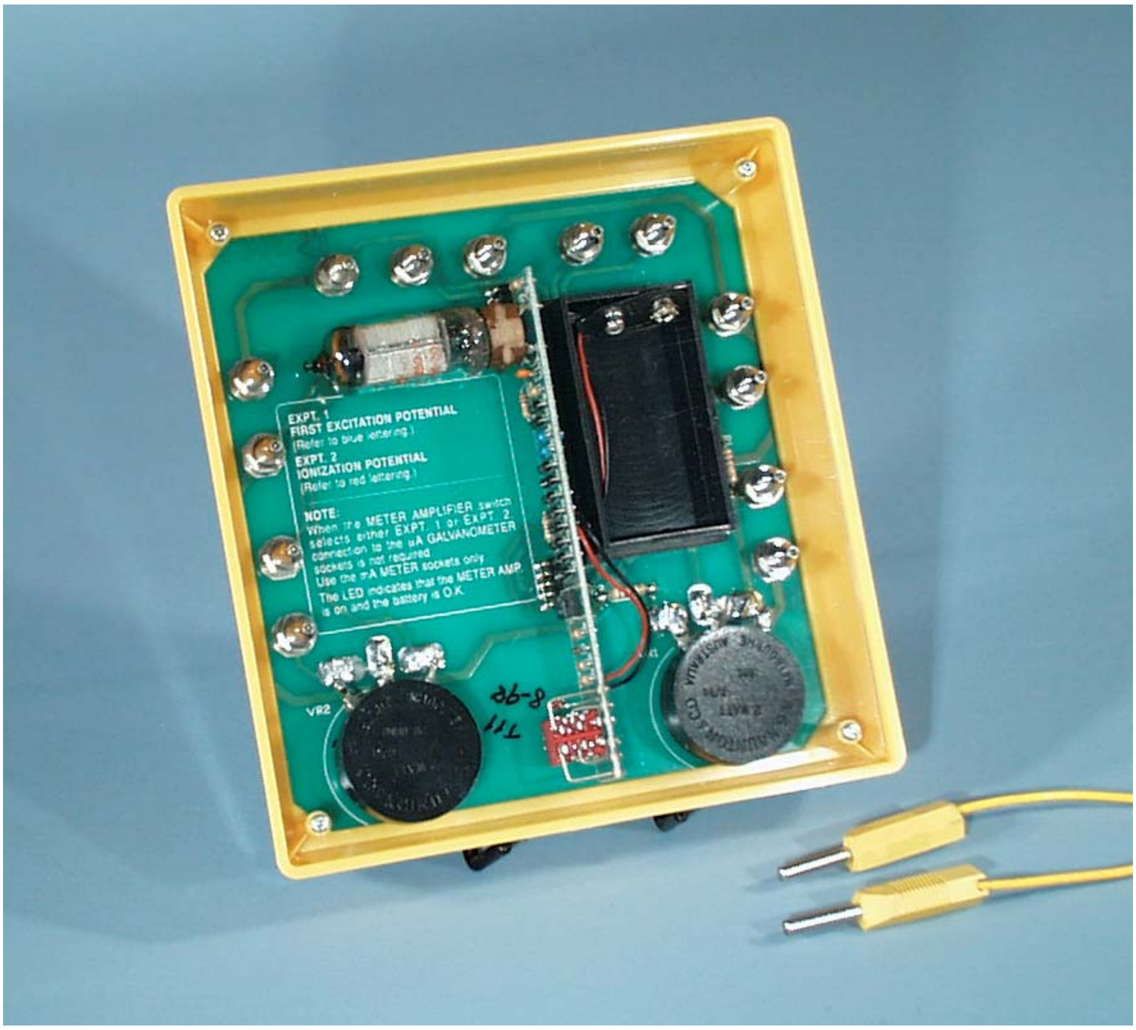
If this happens the Anode current as shown on the microammeter will fall.

It may be asked if the accelerating electrons moving from the Cathode to the Control Grid also collide with and excite XENON atoms. The answer is NO because they start from rest at the Cathode and do not reach full velocity until they reach the Control Grid. It is believed that collisions at speeds below the critical speed result only in perfectly elastic collisions and no energy is lost by the projectile electron and no energy is transferred to the XENON atom.

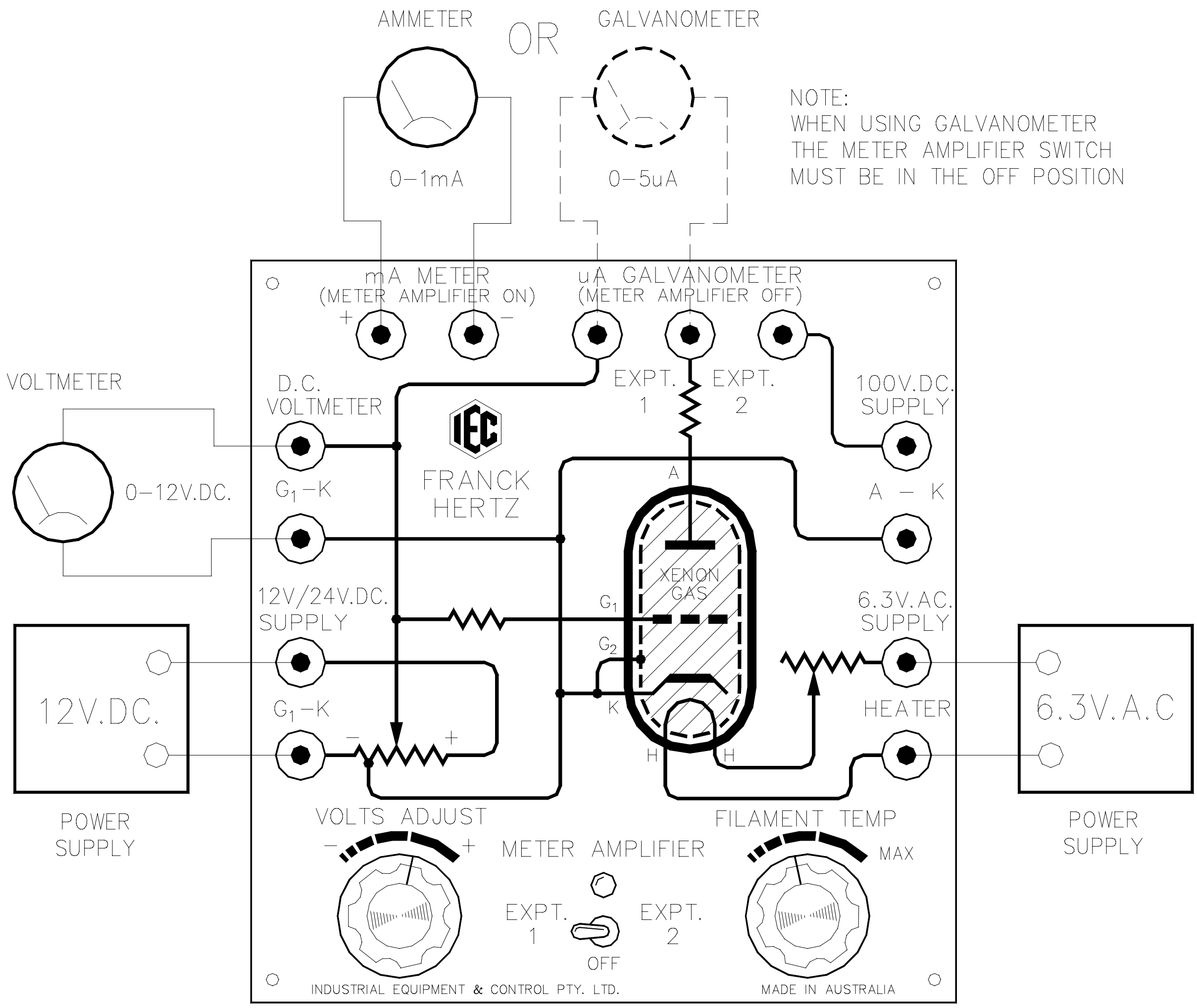
What happens if we increase the Control Grid voltage still further beyond the stage where energy transfers take place ? Electrons will accelerate to even higher velocities such that after a collision, in which the XENON orbital electron is given a lift to a new energy level, the projectile electron still has enough energy to reach the Anode and thus we see the Anode current begin to rise again - **OR** - it may be that before reaching the Control Grid, the projectile electron has reached a velocity sufficient to raise its kinetic energy to the level at which it CAN cause an excitation collision. It then loses exactly that excitation energy, but is then re-accelerated towards the Control Grid and passes through to the Anode.

The rear view of the Franck Hertz apparatus. Showing the holder for the 9V battery and the inbuilt amplifier that converts microamps into milliamps so that a normal student meter can be used for measurements.

The tube filled with Xenon gas is visible plugged into the circuit board.



FIRST EXPERIMENT: The First Excitation Potential of XENON gas

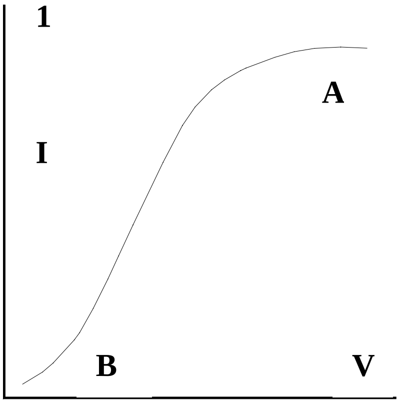


Wire up the circuit as illustrated

Set the heater voltage to Maximum for maximum Cathode heating. Starting from zero, increase the Control Grid potential in steps of 0.5 volt and record the Anode current `IA' for each Control Grid voltage reading.

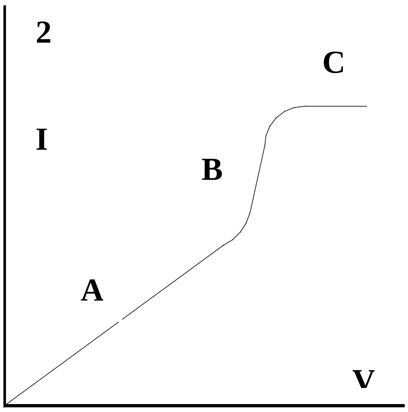
NOTE: Do not exceed 11 volts because collisions at greater than the FIRST excitation may occur and these will introduce factors which will affect the observations. Draw an accurate graph of I vertically against V horizontally.

POSSIBLE FORMS OF THE GRAPH:

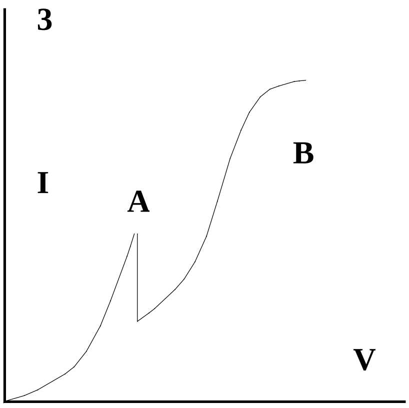


GRAPH 1: If all collisions between projectile electrons were all perfectly elastic, the graph would look like graph#1. This is the normal characteristic curve for a diode in a near vacuum. The only limitation to anode current I (at A) is reached when all electrons being released at the cathode are attracted to the anode. After that, no increase in anode potential will produce more anode current.

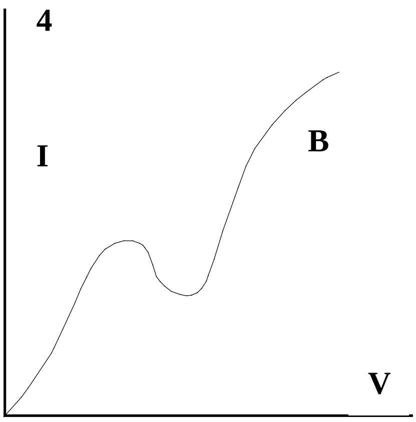
Section B of the graph occurs when some of electrons released from the cathode are repelled back by their slowly moving predecessors (Space Charge Limitation) and when some electrons are captured by the slightly positive control grid.



GRAPH 2: If the projectile electrons could transmit any amount of energy to XENON atoms, for any grid voltage (V) there would be a certain percentage of energy lost in collisions and a straight line section at 'A' would be produced. Section 'B' is reached when all possible XENON atoms have been excited and any increase in V causes a relatively greater increase in I than before. Section 'C' is caused by cathode output limitation.



GRAPH 3: If projectile electrons had exactly the same energy (velocity) and if XENON atoms can accept only a fixed quota (quantum) of energy in the excitation process, a steep drop would occur in I as in section A. This is when all the projectiles have reached this energy level due to V and most of them have lost the energy in excitation collisions.



GRAPH 4: If projectile electrons do not all have the same energy (velocity), while some are capable of imparting the fixed quota of energy (quantum) to the XENON atoms in excitation collisions, other projectile electrons are not capable of making such collisions and thus a rounding off occurs in the shape of graph#3 to become the more rounded shape in graph#4.

In both graph#3 and #4 the assumption is that once having reached the excitation potential (energy level), the projectile can lose just this amount of energy because the XENON atoms can absorb just this amount of energy in the excitation process of having an electron raised from one orbital level to a higher one.

Before this stage is reached, the projectile electrons have insufficient energy to lift an orbital electron to a higher level. Since the Xenon gas atom can accept no less than this minimum energy increase, no excitation can occur, the collision is perfectly elastic and the projectile electrons lose no energy.

After this excitation potential has been reached, the projectile electrons have some energy remaining, even after contributing to the excitation of the XENON atom, therefore they can reach the Anode to cause the Anode current I to rise again in section B of the graph.

QUESTIONS:

In your experiment, what I/V graph do you get ? Graph#1, #2, #3 or #4 ?

What type of collisions are therefore occurring ?

- Totally elastic……no energy transfer ?
- Continuous transfer of energy in any quantity ?
- Transfer of energy only in fixed amounts. That is, in Quanta.

The minimum points on the dips in graphs#3 and #4 indicate the grid potential (and hence the energy of the projectile electrons) that can cause the first excitation of XENON gas.

What is the first excitation potential of XENON gas ?

What is the kinetic energy of these projectile electrons ? Give answer in metres per second and then in kilometres per hour.

If the physical distance in the Thyratron between the Cathode and the accelerating control Grid1 is 2mm, what is the rate of acceleration over that distance in m/sec^2 ?

If the acceleration due to gravity 'g' is 9.8 m/sec^2 , how many 'g's does the electron experience in its dash to collide with a XENON atom ?

If the excited XENON gas atom returns to its former ground state by the orbital electron falling back into its former orbit or energy level, the energy is radiated as electromagnetic radiation. The frequency is given by the formula: $E = hf$ where 'E' is the ENERGY (Joules), 'h' is PLANCK's CONSTANT (6.625×10^{-34} Joules/sec) and 'f' is the frequency.

What will be the frequency of the radiation from the XENON gas ?

In what section of the electromagnetic spectrum will this radiation be found ?

Why is it not visible ?

What would you use to detect it ?

If the velocity of propagation of electromagnetic radiation is the velocity of light, which is 3×10^8 metres/second, what is the wave length of this radiation ?

In graph#3 above, what explanation do you have for the graph not descending to zero at the excitation potential ?

In graph#4 above, what explanation do you have for the graph not descending to zero at the excitation potential ? Hint: The above questions have different answers.

What is a 'Thyratron' ?

How does it differ from any other multi element Valve device (Triode or Tetrode or Pentode) in:

- **Structure ?**
- **Operation ?**
- **Applications ?**

The following tabulation lists the details of shells and orbitals possible therein and then gives the actual numbers of orbital electrons in XENON gas:

SHELL NO	**1**	**2**	**3**	**4**	**5**
Sub shell	s	s,p	s,p,d	s,p,d,f	s,p,d.....
Possible orbitals in sub shell	2	2,6	2,6,10	2,6,10,14	2.6.10......
Actual number of electrons in Xenon atom (54)	2	2,6	2,6,10	2,6,10,14	2,6,10.......

From the above tabulation of actual number versus possible numbers of electrons in XENON gas atom can you postulate what sub shell electrons are affected in the excitation process and to what orbital level they are raised?

SECOND EXPERIMENT: The Ionization Potential of XENON gas.

THEORY:

Bohr's Theory of the structure of the atom is that the nucleus is surrounded by orbiting electrons which can have certain energy levels.

(See Experiment 1)

If the atom is bombarded by particles of sufficiently high energy, or if energy is added to the atom by electromagnetic radiation (X-ray bombardment), it is possible that one or more of the outer orbital (or valence) electrons may become completely detached from the atom with the result that the atom is no longer electrically neutral, but (because it has lost a negatively charged electron) it is now positively charged and has now become a positive ION.

We can then say that the material 'has been Ionized'.

AIM OF THE EXPERIMENT:

The aim of the experiment is to determine the amount of energy that must be provided to a projectile electron to enable it, when colliding with a XENON gas atom, to remove an orbital electron and so to Ionize XENON gas.

Apparatus: We require:

- Source of electrons to act as projectiles.
- The means of accelerating these electrons to high speeds.
- The means of knowing what speeds and energies they have reached.
- The means of determining if they have in fact caused ionizing collisions. Therefore we need a means of determining if positive Ions have been produced.

THE THEORY OF THE EXPERIMENT:

Experiment #2: 'The Ionization Potential of XENON gas'

The heating of the Cathode 'K' by the 6.3V.AC. filament heater boils off electrons from the surface of the Cathode.

These electrons accelerate towards the Control Grid 'G1' and their energy on reaching or passing through the Grid is determined by the potential difference between the Cathode and the Control Grid. This potential is provided by the 0-24V.DC. power source and is measured by the voltmeter. The potential is adjusted by the Grid 'G1-K' voltage control knob.

Some projectile electrons pass through the Grid mesh and collide with XENON gas atoms.

If the Grid to Cathode potential difference is large enough, the projectile electrons may have sufficient energy to ionize the XENON gas atom by knocking off an outer orbital electron.

To determine if such positively charged XENON Ions do exist, it is necessary to separate them from the negatively charged electrons.

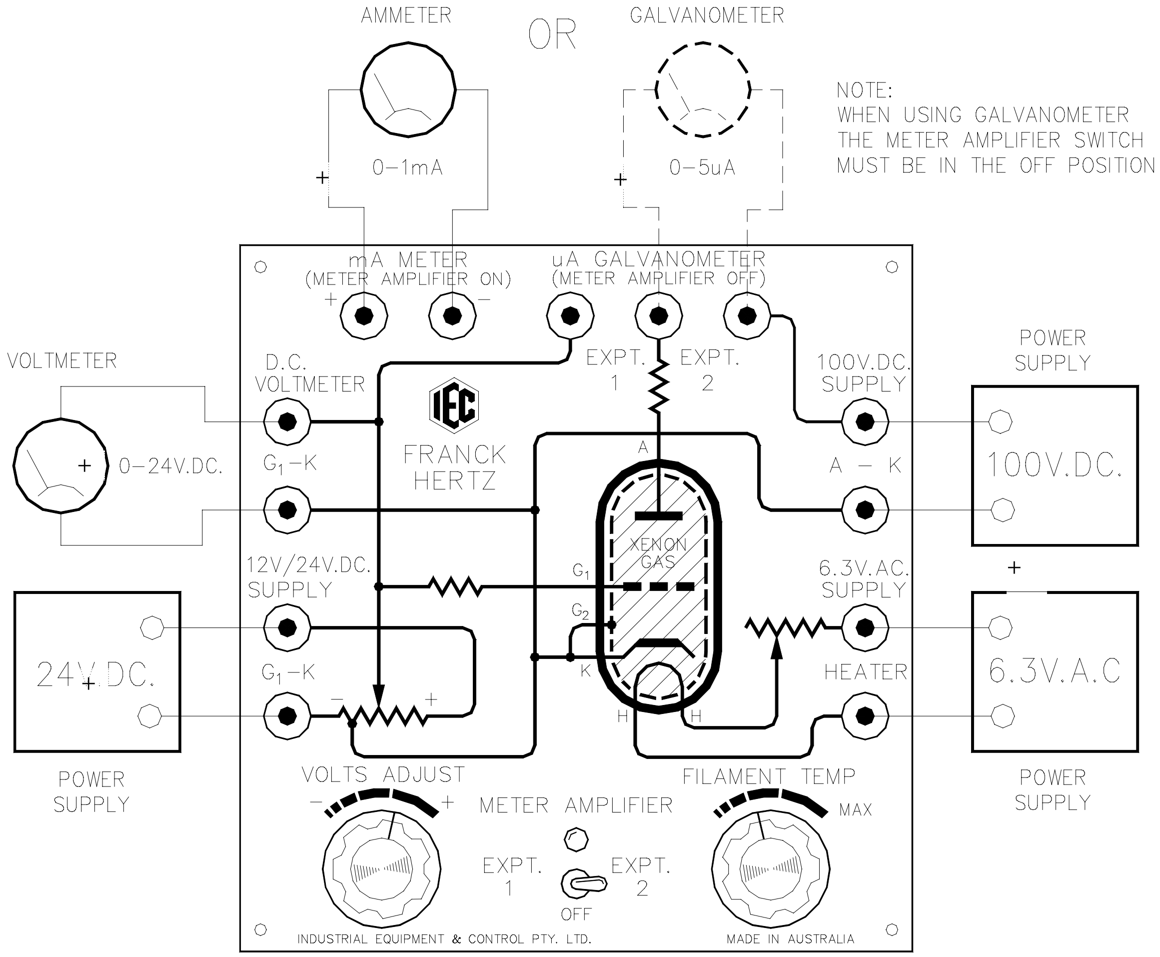
This is done by making the Anode (or Plate) highly negative (at -50V or -100V) relevant to the Grid which is at 0 to +24V, or to the Cathode (which is at 0V). This Anode voltage may be obtained from the IEC power supply normally used for the 'Mass of the Electron' experiment and the same power supply will provide also the 6.3V.AC. supply for the heater.

The electron output from the Cathode is controlled by varying the degree of Cathode heating by altering the filament temperature control knob.

NOTE: The 10k ohm fixed resistors in the Grid and Anode circuits are fitted to limit maximum currents in these circuits. For example, when Ionization of XENON gas occurs, for every XENON Ion produced there is an electron released. These are repelled from the highly negative Anode and pass to the positively charged Control Grid. This increases the current flowing from the Grid. Also, if accidentally the Grid supply voltage were positive and the Anode was also positive, the Thyratron would suddenly 'switch on' and a very large Anode current would flow. The resistors protect the circuits by limiting these currents.

Thyratrons are normally used as 'electronic switches' to control large Anode currents by changing the Grid voltage from negative to positive. They are very useful because almost no power is required for this switching action.

SECOND EXPERIMENT: The Ionization Potential of XENON gas.



Wire up the circuit as illustrated.

Connect microammeter (or Galvanometer). Be careful of the polarity.

Connect the voltmeter to measure and record Control Grid potential.

Apply 0-24V.DC. power source (Be careful of polarity).

Apply -50V.DC. (or -100V.DC.) Anode voltage (negative to Cathode).

Apply 6.3V.AC. to the FILAMENT TEMP. sockets.

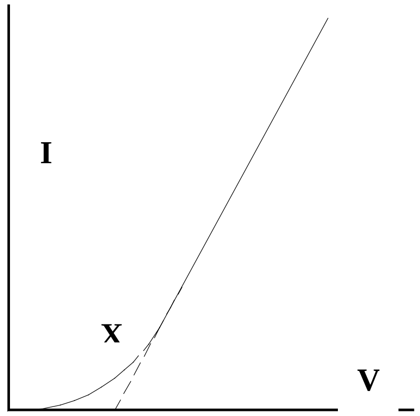
Set the Control Grid voltage to 15V as indicated on the voltmeter.

Slowly raise current through the heater by the FILAMENT TEMP. control knob until a maximum Anode current reading on the Galvanometer is observed.

NOTE: The temperature of the Cathode does not respond immediately to changes in the heater current. After adjusting the heater current, wait several seconds until its effect is observed before altering it again. **This is a slow but very necessary procedure.** The maximum Anode current should be approximately 1 microamp at 15V Grid potential.

Leaving the heater current set, now reduce the Control grid voltage to zero.

In small steps (0.5V), increase the Control Grid potential from 0 to about 20V and record the Anode current for each Control Grid potential.



Draw a graph of I (Anode current) against V (Grid potential)

The graph will probably take the form as shown:

Erratic readings may be seen at about 14V. These are explained as the changes in energy levels as electrons in inner shells (lower energy levels) are energised to take up the level of the electrons removed from an outer orbital shell during the Ionization collisions.

Extend the straight portion of the graph backwards to cut the V horizontal axis. The point of intersection `X' indicates the potential at which Ionization commences. This is the Ionization potential of XENON gas.

QUESTIONS:

What is the energy of a projectile electron which Ionizes a XENON gas atom ? Remember that 1 volt is 1 Joule (1 Newton Metre) per 1 Coulomb of charge and 1 Coulomb is 6.25 x 10^{18} elementary charges.

Give the answer both in Electron Volts (eV) and in Joules.

If the mass of the electron is 9.1x10^{-31} kg., what is the velocity of this projectile electron when it makes its Ionizing collision ?

Give the answer in metres per second and then convert this to kilometres per hour.

What is the frequency of the electromagnetic radiation that would have sufficient energy to ionize XENON ?

The energy of a photon = hf where ‘h’ = Plank's constant (6.626 x 10^{-34} J.sec.) and ‘f’ = frequency of radiation.

What is the wave length of this Ionizing radiation ?

Remember, Velocity = ‘f’x’l’ and the velocity of light (and all other forms of electromagnetic radiation) is 3 x 10^{8} metres per second.

Give the answer in both Angstroms and millimicrons.

In what part of the electromagnetic spectrum would this radiation lie ?

- Gamma Rays ?
- X-Rays ?
- Ultra violet ?
- Violet ?
- Blue ?
- Green ?
- Yellow ?
- Orange ?
- Red ?
- Visible waves ?
- Heat waves ? (Infra red)
- Micro waves ? (Radar)
- Ultra High Frequency radio waves ? (UHF)
- Very High Frequency radio waves ? (VHF)
- Short Wave radio ?
- Long Wave radio ?

Designed and manufactured in Australia