THE INSTITUTE OF EDUCATION

Physics

PAT DOYLE

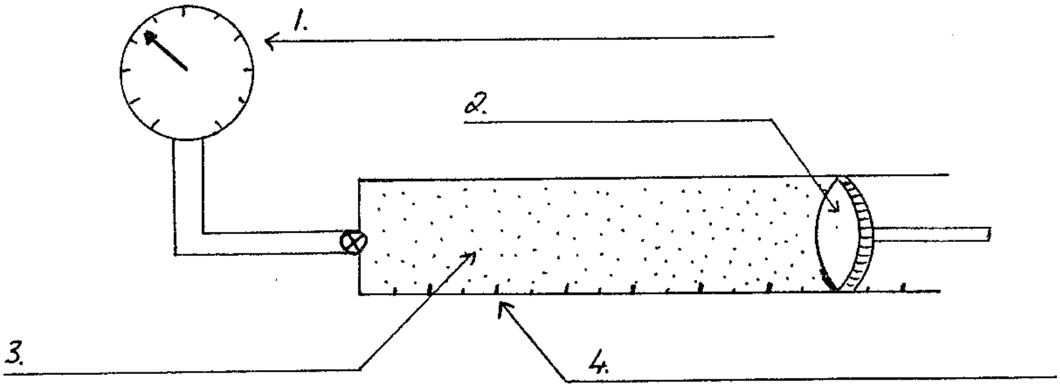
LEAVING CERTIFICATE

HIGHER LEVEL

6TH YEAR

BOYLE'S LAW

Mandatory experiment: experiment to verify Boyle's law:



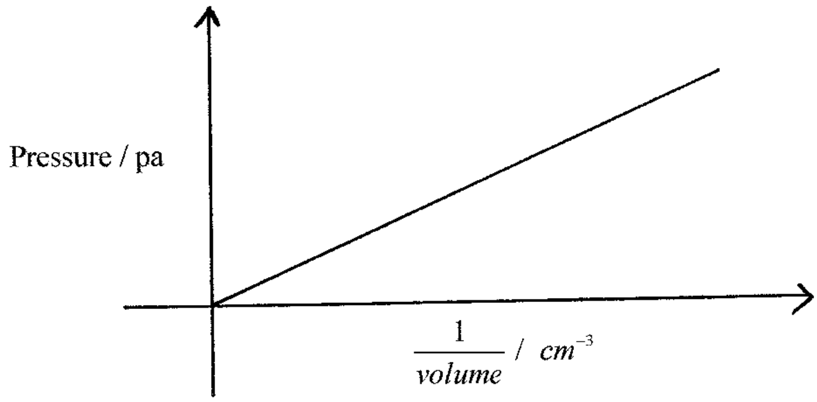
- By adjusting the gas-tight piston you will change both the volume and the pressure of the gas.

Data:

- The volume of the gas is read from the scale along the side of the cylindrical container. It is acceptable to record the value of volume in cm^3
- The pressure of the gas is read from the pressure gauge. The pressure is in Pa.

Calculations:

- Measure and record several values of pressure and corresponding values of volume.
- Plot a graph of pressure on the y-axis and the **reciprocal of volume** on the x-axis.
- A straight line graph through the origin verifies $p \propto \frac{1}{V}$. Boyle's law verified !!!



Accuracy:

- When the piston is adjusted for another set of readings allow the gas to settle for a few minutes. This allows the gas to return to room temperature. This keeps the **temperature of the gas constant**. (we assume room temperature is constant !!!)
- Using a gas-tight piston keeps the **mass of the gas constant**.
- Avoid the error of parallax when reading the pressure gauge and when reading the volume of the gas from the calibrated scale along the cylinder.
- Avoid very small values of volume as they result in greater percentage errors when used in calculations.

Sample question 8: (2003) In an experiment to verify Boyle's law, a student measured the volume *V* of a gas at different values of the pressure *p*. The mass of the gas was not allowed to change and its temperature was kept constant. The table shows the data recorded by the student.

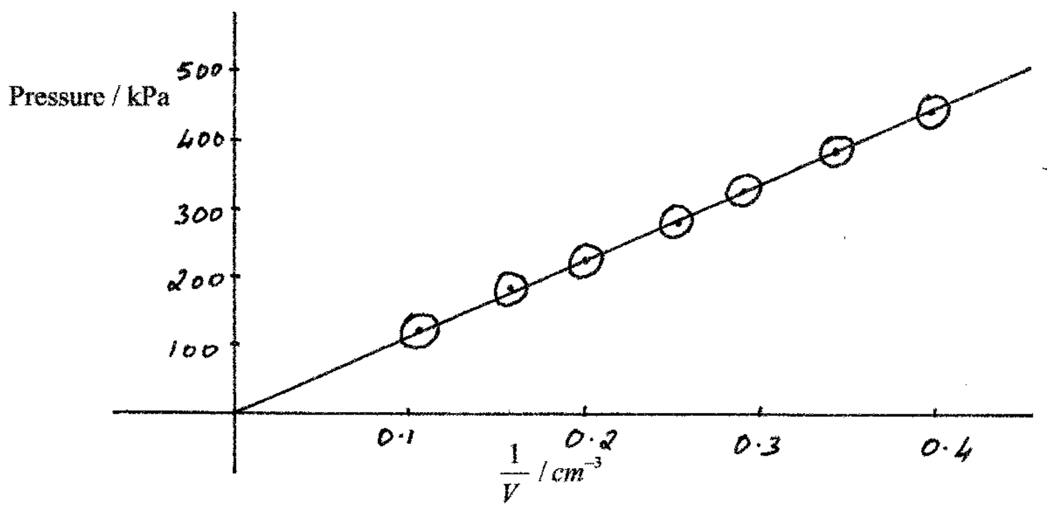
p/ kPa	120	180	220	280	320	380	440
$V/\ cm^3$	9.0	6.0	5.0	4.0	3.5	3.0	2.5

Draw a suitable graph on graph paper to show the relationship between the pressure of the gas and its volume.

Explain how your graph verifies Boyle's law

Solution: The graph is pressure against **reciprocal of volume.** The data table becomes

p/ kPa	120	180	220	280	320	380	440
$\frac{1}{V}/cm^{-3}$	0.111	0.167	0.2	0.25	0.286	0.333	0.4



Explain…….. The straight line graph through the origin verifies that pressure is inversely proportional to volume for the fixed mass of gas at a fixed temperature i.e. Boyle's law is verified.

Sample question 9: (2011)

During an experiment to verify Boyle's law, the pressure of a fixed mass of gas was varied. A series of measurements of the pressure *p* and the corresponding volume *V* of the gas was recorded as shown. The temperature was kept constant.

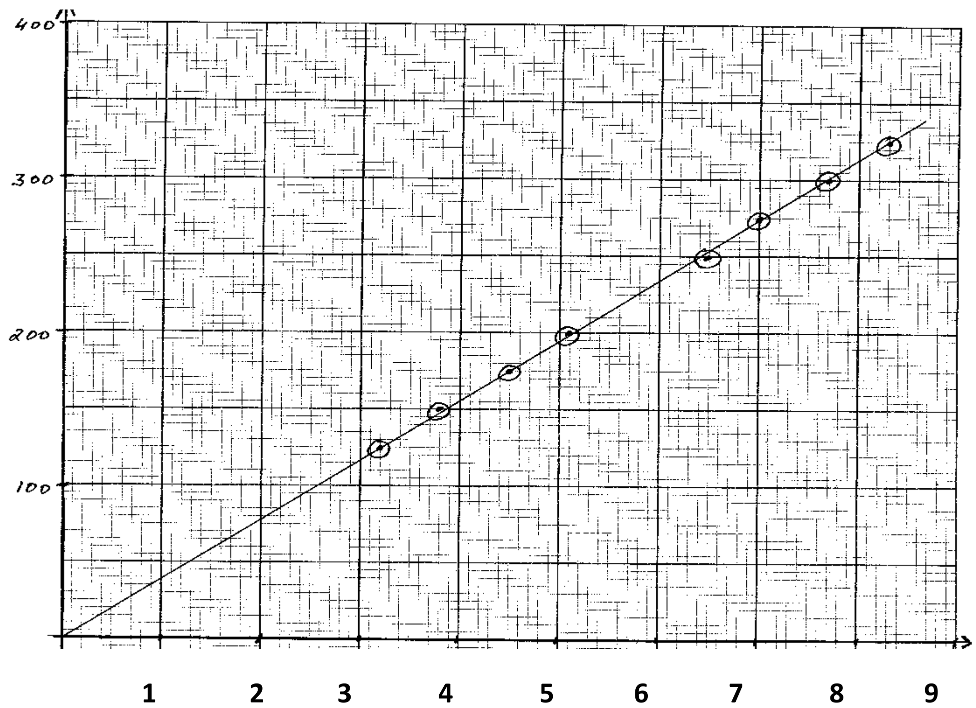
p/kPa	325	300	275	250	200	175	150	125
$V/\ cm^3$	12.1	13.0	14.2	15.5	19.6	22.4	26.0	31.1

Draw a suitable graph to show the relationship between the pressure and the volume of a fixed mass of gas. Explain how your graph verifies Boyle's law.

Solution: Plot a graph of pressure against the **reciprocal of volume**

$p\ /\ kPa$	325	300	275	250	200	175	150	125
$\frac{1}{V}/cm^{-3}$	0.083	0.077	0.070	0.065	0.051	0.045	0.038	0.032
$\frac{1}{V}\times 10^{-2}\ /cm^{-3}$	8.3	7.7	7.0	6.5	5.1	4.5	3.8	3.2

Pressure / k Pa

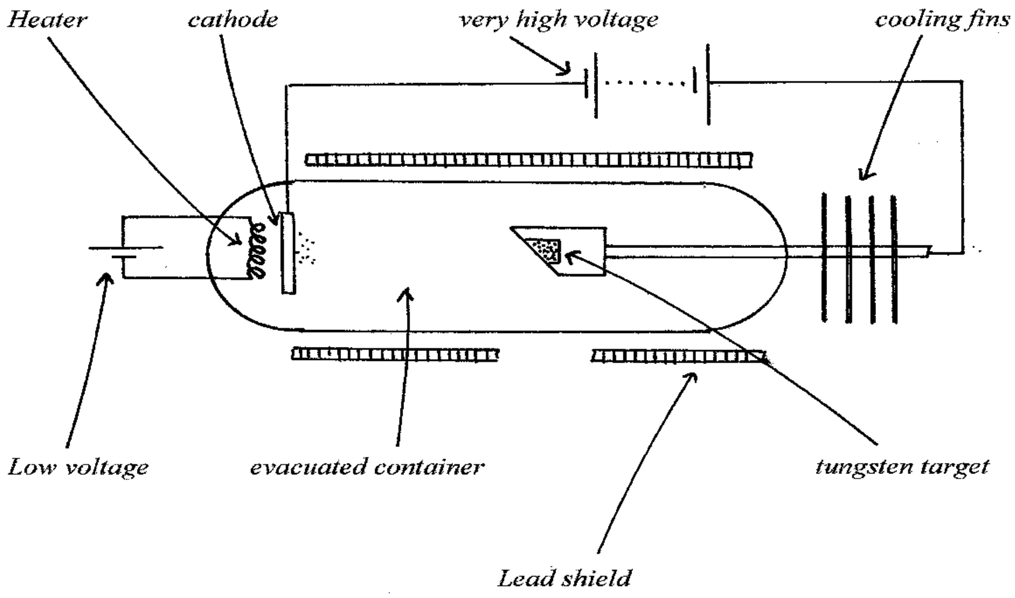


$\frac{1}{volume}\times 10^{-2}\ /\ cm^{-3}$

Note: The straight line graph through the origin verifies that $P \propto \frac{1}{V}$

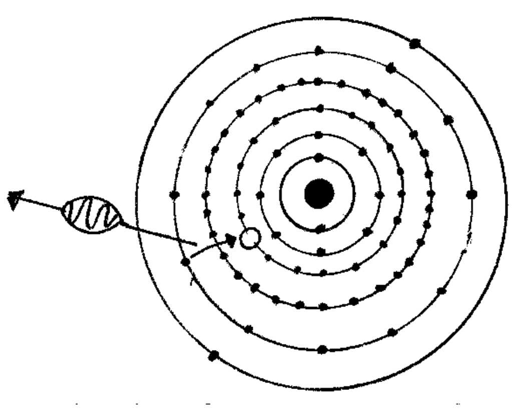
X - Rays

Making x – rays:



- Electrons are emitted from the cathode by the thermionic effect.
- They are accelerated to a very high speed by the high voltage
- They hit the tungsten target and X-rays are emitted
- The lead shield protects the user from the harmful effects of X-rays.

The atomic view:



- When high speed electrons hit the tungsten anode some are energetic enough to penetrate into an inner electron orbit and dislodge an inner electron.
- An outer electron falls into the gap due to the missing electron, i.e. an outer electron falls to a lower energy level.
- The excess energy of this electron is emitted as a photon and this photon is an X-ray.

Heat energy:

- About 99% of the energy of the electrons becomes heat energy when they hit the tungsten.
- Tungsten has a high melting point and fortunately does not melt.
- The tungsten is set in copper and the heat is conducted to the outside of the tube to the cooling fins.
- These fins have a large surface area and the heat escapes off into the air.
- Some X-ray tube have a liquid cooling system.

Historical Note : X-rays were discovered in 1895 by the German physicist W. Rontgen.

Intensity of an X-ray beam :

- The intensity of an X-ray beam refers to the **number** of X-rays in the beam.
- The number of X-rays required depends on the surface area of the item to be examined. The X-ray of a hand would require more X-rays than the X-ray of just a single finger.
- Intensity depends on

  → Number of electrons crossing the tube

  → This depends on the temperature of the heating coil

  → This depends on the current from the low voltage battery

Penetration (Hardness) :

- The penetrating power of the X-rays refers to the ability of the X-rays to pass through different thicknesses of material or different densities of material.
- A leg X-ray would need to be more penetrating than a finger X-ray.
- Penetration depends on

  → Speed of electrons crossing the tube

  → This depends on the value of the high voltage

Practical uses:

- Damaged tissue in the lungs has a greater density than healthy tissue. Since penetration of X-rays is better for less dense materials, damaged tissue absorbs more X-rays and shows up as a darker region (cloud) on an X-ray photograph.
- X-rays can be used to locate flaws in metals, e.g. a crack in the body of an airplane.

Note on the X-ray tube :

- The glass tube has an extremely low pressure inside, i.e. there is very little gas inside the tube.
- This means that electrons emitted from the cathode can travel to the anode with a very small probability of a collision with a gas molecule on the way.
- Such collisions would only slow down the electrons

X-rays and the photoelectric effect : It is often said that one process is the inverse of the other.

X-ray	photoelectric effect
$\rightarrow$ *electrons in and photons out*	$\rightarrow$ *photons in and electrons out*
$\rightarrow$ electrons hit the tungsten target and photons are emitted	$\rightarrow$ photons fall on a metal and electrons are emitted

Math Note : (i) Since X-rays are photons, higher energy X-rays mean higher frequency X-rays.

Remember $E = h \times f$

(ii) kinetic energy of electron = energy of photon

$$\frac{1}{2} m v^2 \quad \text{or} \quad q\,V \quad = \quad h\,f \quad \text{or} \quad \frac{h\,c}{\lambda}$$

Sample question 1: (i) Calculate the kinetic energy gained by an electron when it is accelerated through a potential difference of 50 kV in an X-ray tube.

(ii) Calculate the minimum wavelength of an X-ray emitted from the anode.

(Planck constant = 6.6 × 10^{-34} J s; speed of light = 3.0 × $10^{8}\, m s^{-1}$;

charge on electron = 1.6 × 10^{-19} C)

Solution: (i) gain in kinetic energy is given by

$$E = q \times V$$
$$= 1.6 \times 10^{19} \times 50 \times 10^{3}$$
$$= 8 \times 10^{-15} \; Joule$$

(ii) Assume all kinetic energy of electron becomes energy of X-ray photon i.e.

$$E = \frac{h\,c}{\lambda}$$
$$\lambda = \frac{h\,c}{E}$$
$$= \frac{6.6 \times 10^{-34} \times 3 \times 10^{8}}{8 \times 10^{-15}}$$
$$= 2.475 \times 10^{-11}\, m$$

Note: Energy of a photon is inversely proportional to the wavelength of the photon. Therefore minimum wavelength corresponds to maximum energy i.e. all the energy of the electron.

Sample question 2: (i) When electrons hit the target in an X-ray tube, only a small percentage of their energy is converted into X-rays. What happens to the rest of their energy and how does this influence the type of target used?

(ii) A potential difference (voltage) of 40 kV is applied across an X-ray tube. Calculate:

(a) the maximum energy of an electron as it hits the target

(b) the frequency of the most energetic X-ray produced.

(Plank constant = 6.6 × 10^{-34} J s ; charge on electron = 1.6 × 10^{-19} C)

Solution: (i) The majority of the energy of the electron is converted to heat when they hit the anode. The target metal (anode) must have a very high melting point, e.g. tungsten.

(ii) (a) energy of accelerated electron = $q\ V$

$$= 1.6\times10^{-19} \times 40000$$

$$= 6.4\times10^{-15}\ joule$$

(b) energy of an X-ray = $h\ f$

Rearrange to get $f = \dfrac{energy}{h}$

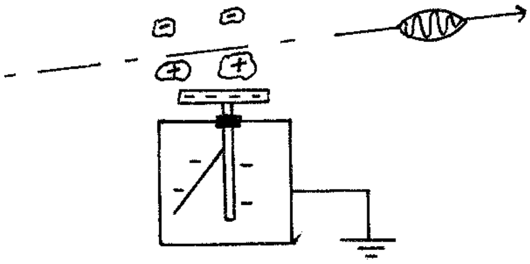
$$f = \frac{6.4\times10^{-15}}{6.6\times10^{-34}}$$

$$f = 9.7\times10^{18}\ Hz$$

Note: Even though most of the energy of the electron is not given to the x-ray we assume that it is . This is because of the word “most” in the question.

Properties of X-rays:

- The speed of an X-ray is the same as the speed of light in a vacuum. ($3\times10^{8}\,ms^{-1}$)
- They ionise the molecules of a material through they pass. X-rays are regarded as **ionising radiation**



- If the air molecules above a negatively charged gold leaf electroscope are ionised then the positive ions would come in contact with the cap of the electroscope. The charge on the electroscope would be reduced. The deflection of the gold leaf would decrease.
- X-rays are not deflected in magnetic fields and are not deflected in electric fields. Therefore X-rays have no charge and are neutral
- X-rays cause a chemical reaction with film in a similar way to light. X-ray photographs are therefore possible.
- X-rays have a very high frequency and will eject electrons from a metal surface by the photoelectric effect. X-rays would exceed the threshold frequency of many metals.
- X-rays can cause fluorescence i.e. they strike certain substances and emit photons of a longer wavelength, very often photons of visible light.

Dangers of X-rays:

- X-rays can rearrange the molecular structure of certain materials. A harmless substance in the body could becomes a harmful substance
- X-rays can kill individual cells in the human body. If a large number of cells are damaged then the tissue could be damaged beyond repair
- Excessive doses of X-rays could lead to certain forms of cancer.

What is an X-ray ????

- A photon is a discrete quantity of electromagnetic radiation
- An X-ray is a photon of electromagnetic radiation of very high frequency. !!!!!!!!!!!!!!