Year 12 Physics

# Atomic Physics

# Models

# Models

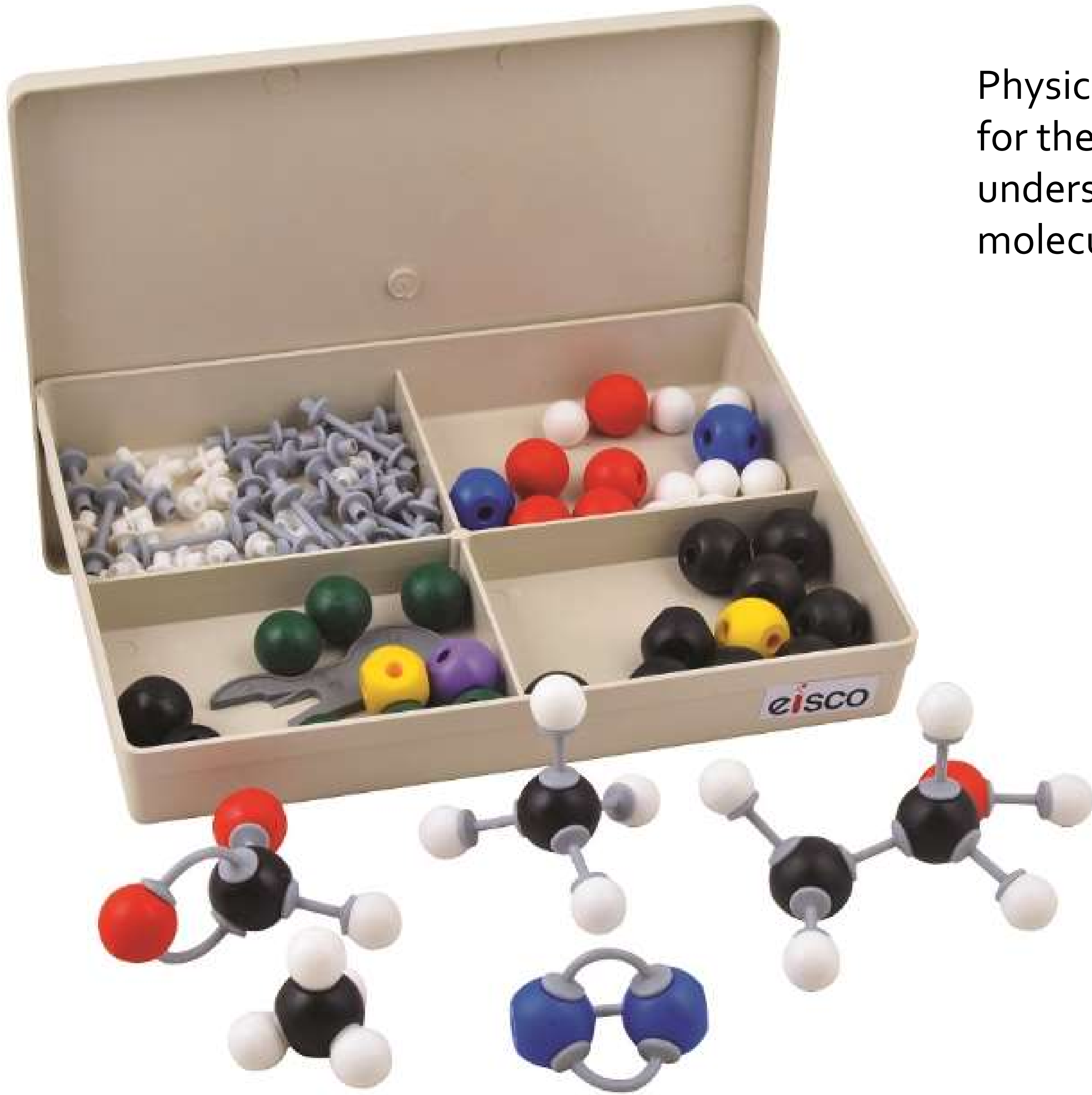
In science, a model is a representation of an idea, an object or even a process or a system that is used to describe and explain phenomena

# Models

Come in a variety of forms:

- Physical
- Conceptual
- Drawings & illustrations
- Mathematical
- Games

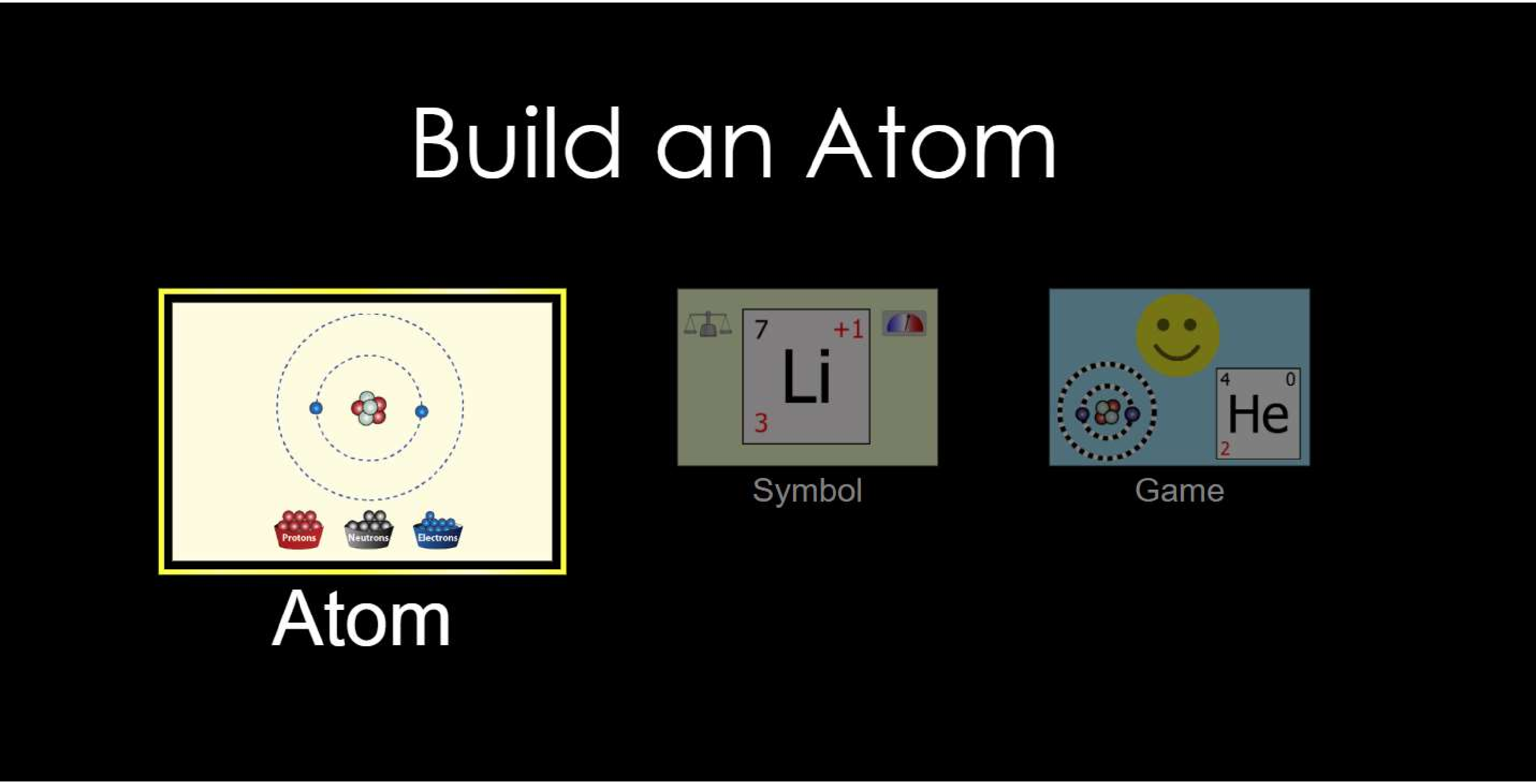
…and many more




Physical 3D model of atoms for the purpose of understanding bonding and molecules

$$\boldsymbol{F} = \boldsymbol{ma} = \frac{\Delta \boldsymbol{p}}{\Delta \boldsymbol{t}}$$

Mathematical model of motion for the purpose of understanding how change in motion happens




Mathematical model of atomic structure for the purpose of understanding how the variety of elements comes about

# Models

All models are wrong because they must be

- Oversimplified
- Contain obvious mistakes that have to be ignored

Models are useful because

- They do capture some essential features of the systems being modelled which aids the understanding of those systems

# Modelling as the scientific method

- It can be considered that science is all about modelling the universe
- The progress of science is that of refining and improving our models
- Better models explain more and predict new things
- The exact sequence of improvement is variable (the old scientific method flow chart is way to simple).

# Science and models of the physical world

- We do not claim to know the absolute nature of the basic components of matter.
- Our models changed over time in some details, but the basic picture is agreed now and is called the Standard Model.
- But it has to be wrong…

# Is Physics complete? No.

- The standard model does not incorporate gravity
- We don’t know what happens to the gravitational field that belongs to a particle like an electron when it start to behave as a wave (as in electron diffraction).

- Gravity is described by Einstein’ s theory of general relativity – a continuous field

- Atoms & light are described by Quantum mechanics – discrete fields

- Solve that problem and get your own Nobel Prize

# Science and models

- One important thing we have chucked away is the idea of certainty. It seems that reality is a little blurry.

- Another thing that went out the window was the idea that the world is really as we experience it to be. It is a whole lot more.

[redacted]

[redacted]

# Module 8: From the Universe to the Atom

## Outcomes

**A student:**

- analyses and evaluates primary and secondary data and information PH11/12-5
- solves scientific problems using primary and secondary data, critical thinking skills and scientific processes PH11/12-6
- communicates scientific understanding using suitable language and terminology for a specific audience or purpose PH11/12-7
- explains and analyses the evidence supporting the relationship between astronomical events and the nucleosynthesis of atoms and relates these to the development of the current model of the atom PH12-15

## 8.2 Structure of the Atom

**Inquiry question:** How is it known that atoms are made up of protons, neutrons and electrons?

Students:

- investigate, assess and model the experimental evidence supporting the existence and properties of the electron, including:
  - early experiments examining the nature of cathode rays
  - Thomson's charge-to-mass experiment
  - Millikan's oil drop experiment (ACSPH026)
- investigate, assess and model the experimental evidence supporting the nuclear model of the atom, including:
  - the Geiger–Marsden experiment
  - Rutherford's atomic model
  - Chadwick's discovery of the neutron (ACSPH026)

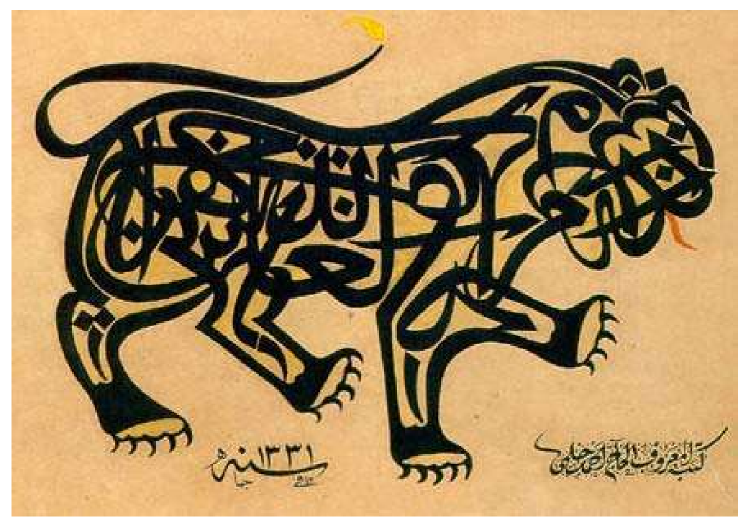
# Dalton

# Democritus (460-370 BC)

- The earliest mention that we know of the idea of the atom comes from Ancient Greece.
- Democritus of Abdera, in Thrace
- Biographical Details Here

# Abu Hāmed Mohammad ibn Mohammad al-Ghazzālī (aka Algazel) (1058-1111)

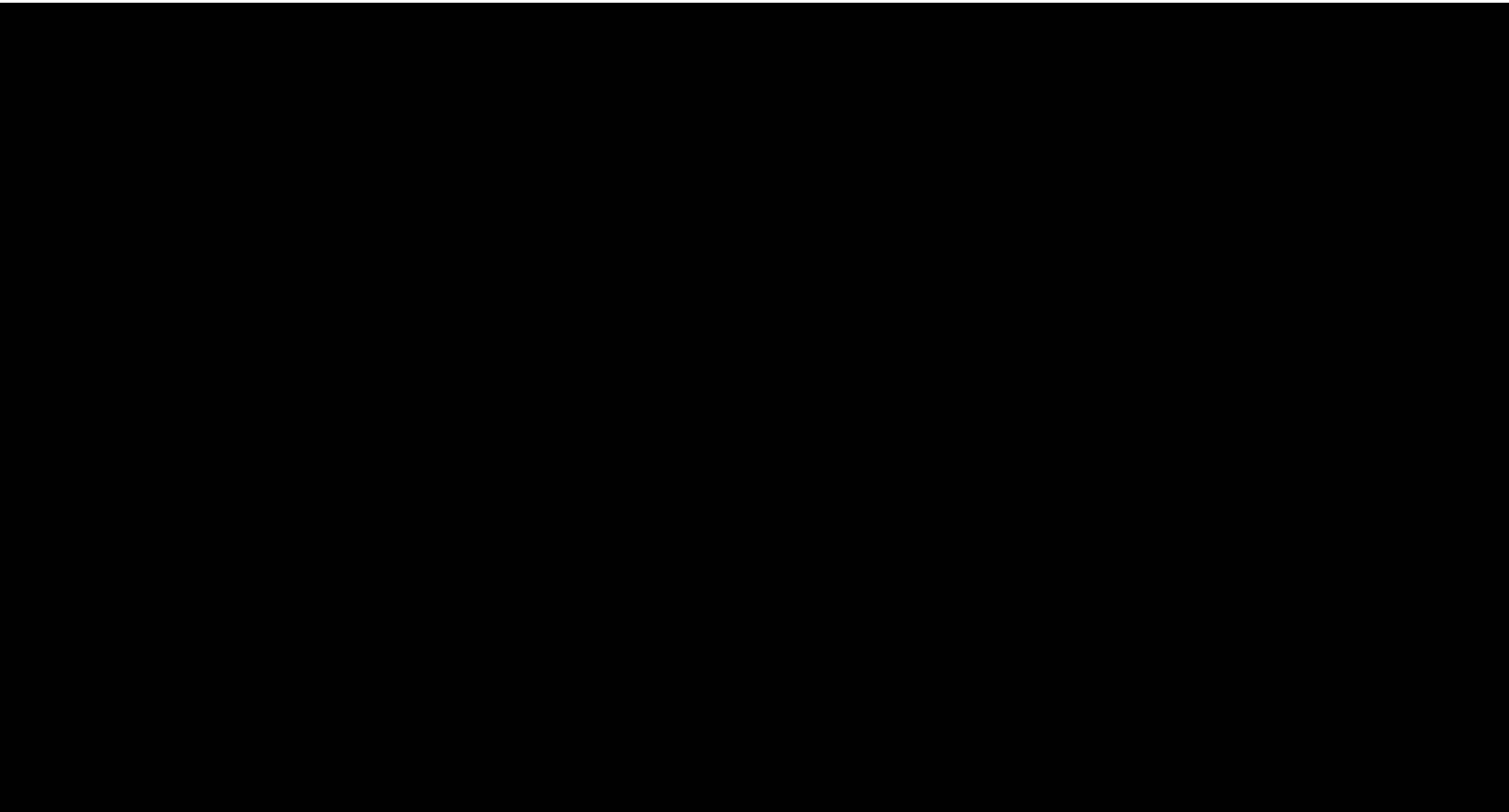
- Islamic mystic who wrote about a picture of reality that had many features of atomic theory
- Not that anyone did anything with this idea for a long time, except ignore it



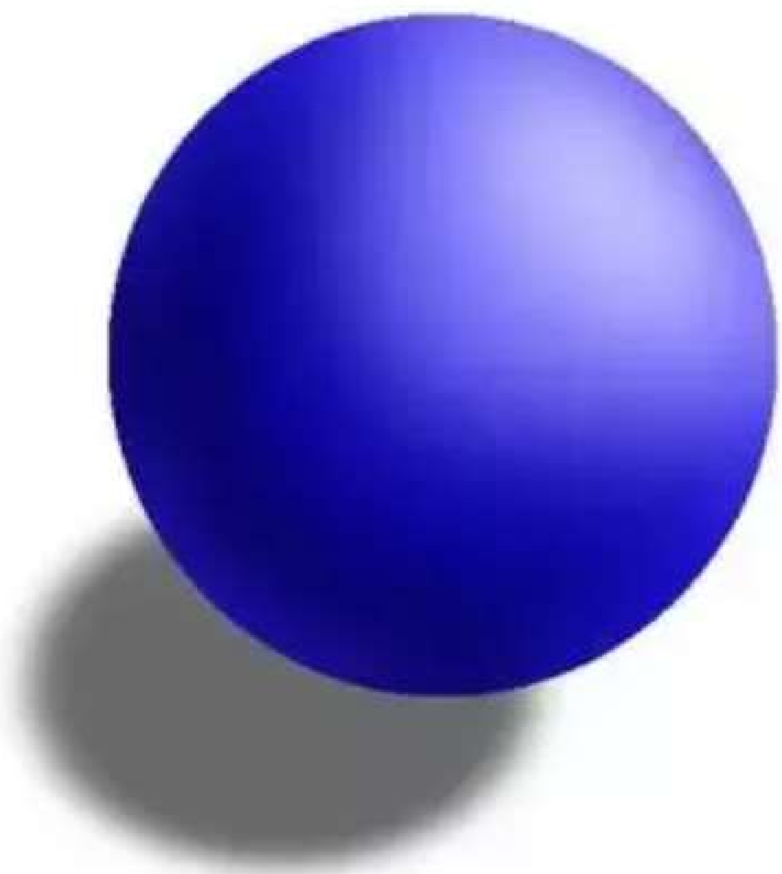
# John Dalton (1766–1844)

## HIS CONTRIBUTION

Added to our understanding of the nature of the elements through the proposition that matter might be composed of small indivisible units called atoms.



# John Dalton (1766–1844)



# Dalton summary

## STRENGTHS

Explains two chemistry laws:

- Conservation of mass
- law of constant proportions

## WEAKNESSES

Does not explain:

- Atomic stability, radioactivity, atomic size, isotopes, ions, cathode rays, atomic spectra, shapes of molecules, scattering of alpha particles by foils, electron diffraction
- allotropes of elements e.g. carbon as diamond or graphite
- How molecules form – no bonding mechanism
- How atoms interact – no forces
- gravity
- Masses of atoms
- The particle zoo (neutrinos etc)
- Structure of periodic table

# J. J. Thompson(1856–1940)

HIS CONTRIBUTION

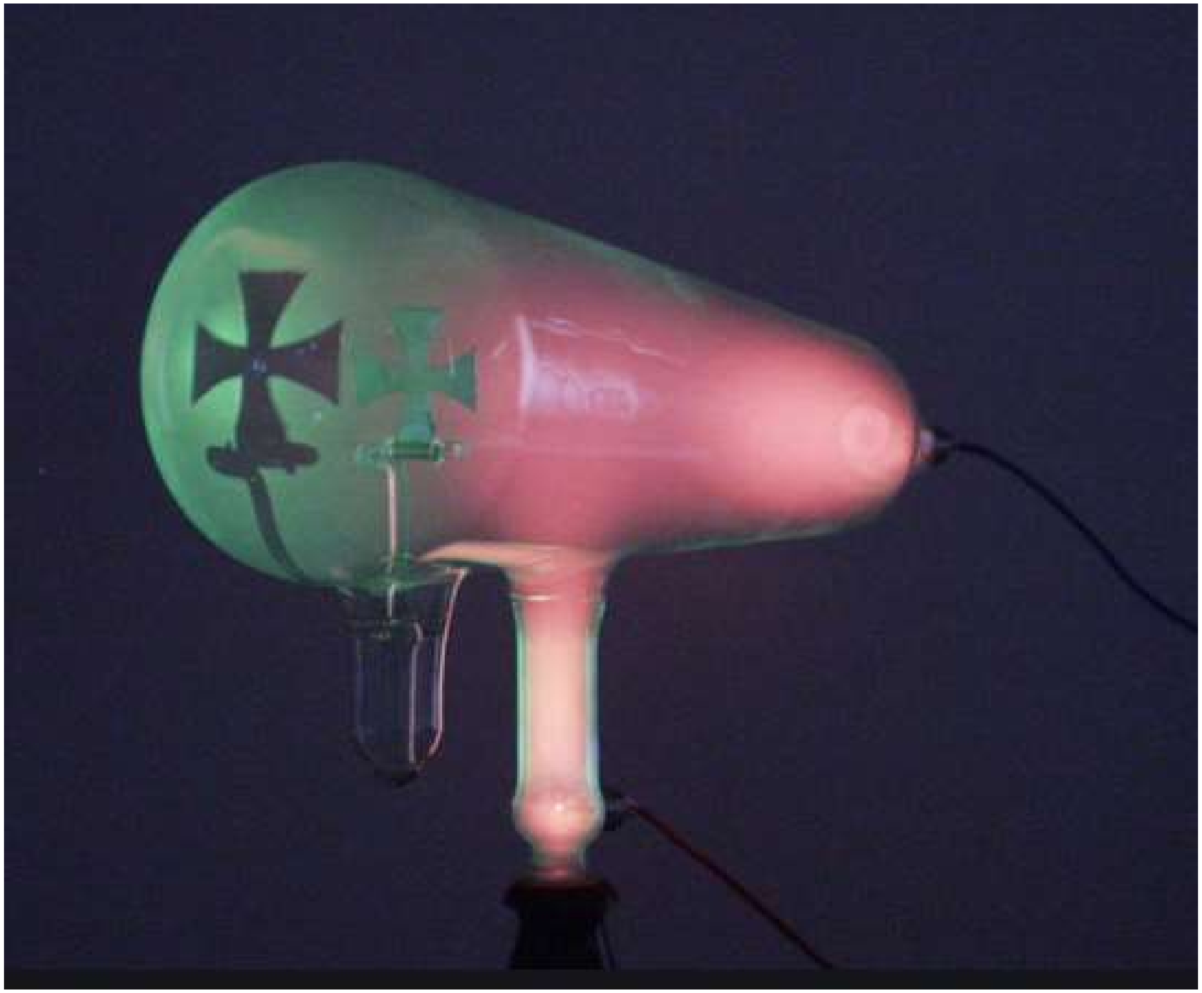
Added to our understanding of the nature of the atom through the **discovery of the electron**.

Set out to determine the nature of cathode rays

# Cathode Rays

- Prior to the discovery of electrons, the atoms was though to be indivisible. It comes from the Greek word *atomos*, which means indivisible. The discovery of electrons showed that atoms were actually composed of smaller components.
- A cathode ray tube is a sealed glass tube which is mostly vacuum, with two electrodes inside arranged as an electron gun. Electrons are released from a negative terminal (i.e. cathode) and are accelerated across a potential difference towards a positive terminal (i.e. anode).
- In 1897, Joseph John (J.J.) Thomson was studying electric discharges from cathode ray tubes when he found that the tube glowed more when the gas was at a lower pressure. When the tube was painted with phosphorescent paint, the paint opposite the negatively charged cathode glowed. When he placed two electrically charged plates above and below the cathode ray tube, the ray deflected towards the positively charged plate, indicating the beam was negatively charge. The same beam emerged even when he changed the material of the cathode.

# Cathode Rays



# Cathode ray tube

- Glass tube containing gas
- Electrodes at each end – very high voltage
- Glowing ‘rays’ emanate from the cathode (negative terminal)

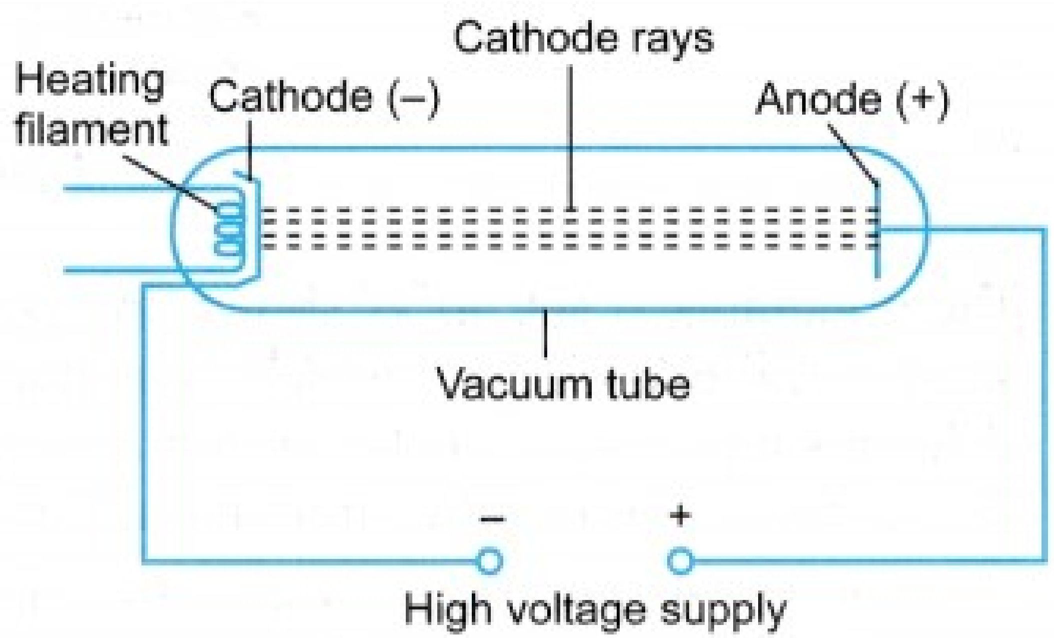
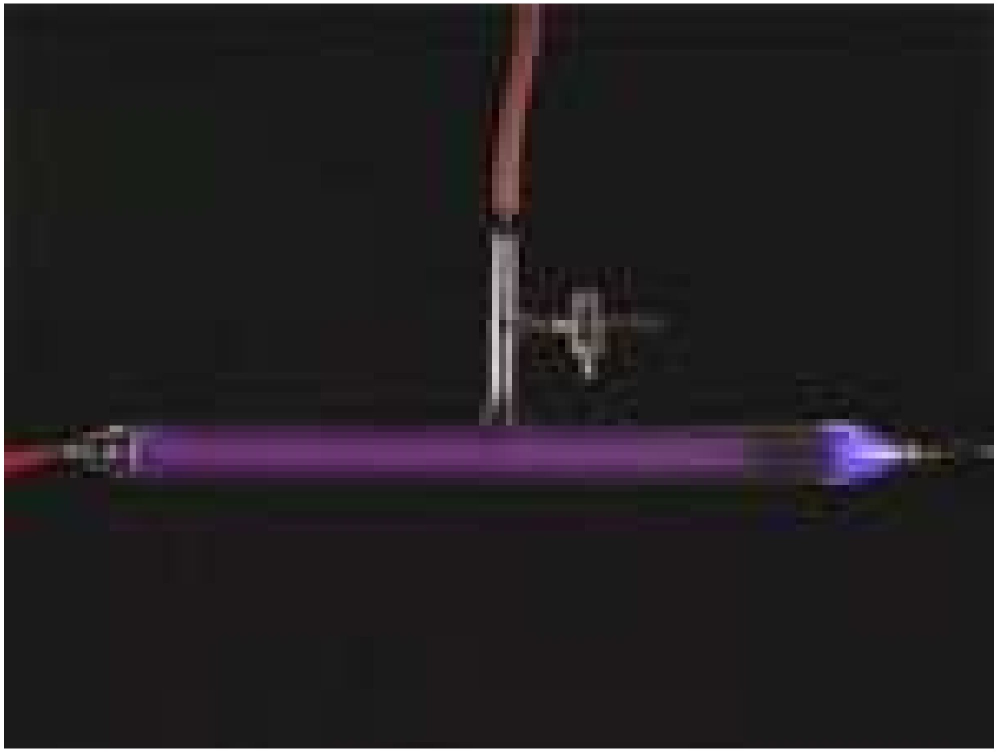



***Figure*** *Vacuum tube*

# Discharge tubes

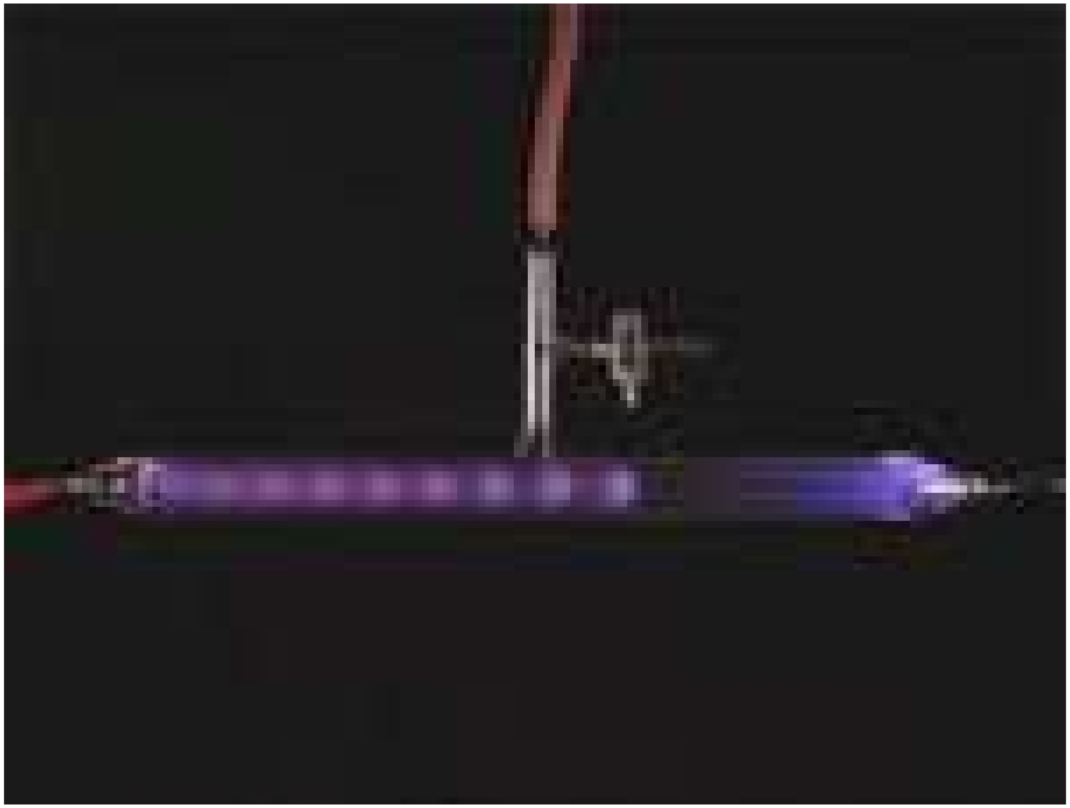
- The next few slides are photos of discharge tubes showing the cathode rays that are produced as the pressure in the tube is reduced.

# Geissler discharge tubes



**Pressure: 5.33 kPa**

# Geissler discharge tubes



**Pressure: 0.798 kPa**

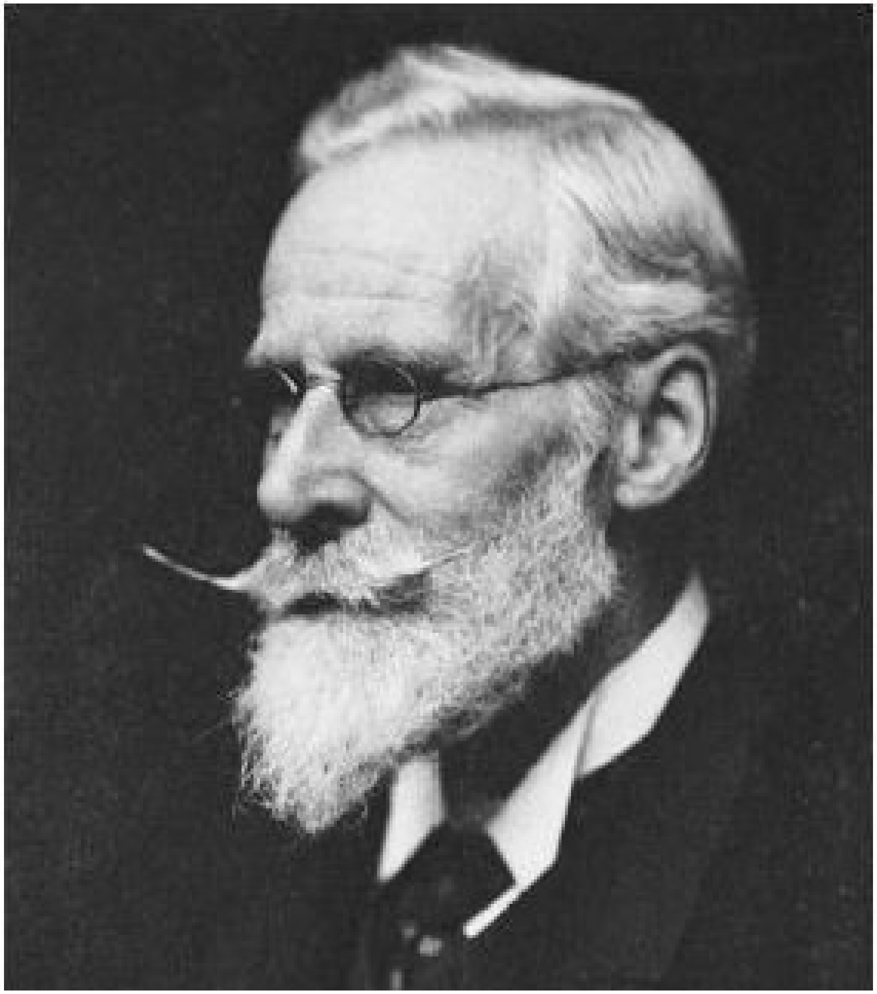
# Geissler discharge tubes

**Pressure: 0.019 kPa**

# Geissler discharge tubes

**Pressure: 0.004 kPa**

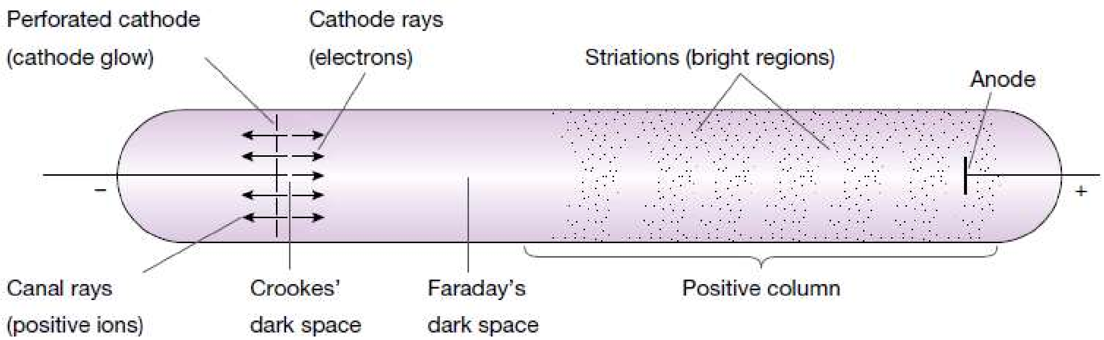
# WILLIAM CROOKES

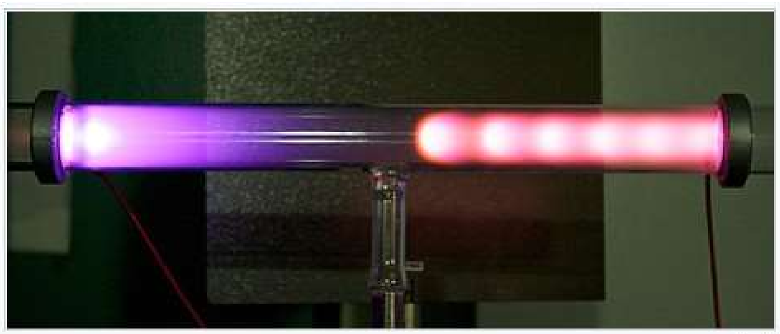


**Sir William Crookes** (17 June 1832 – 4 April 1919) was a British chemist and physicist who attended the Royal College of Chemistry[1] in London, and worked on spectroscopy. He pioneered vacuum tubes, inventing the Crookes tube which was made in 1875. This was a foundational discovery that eventually changed the whole of chemistry and physics.

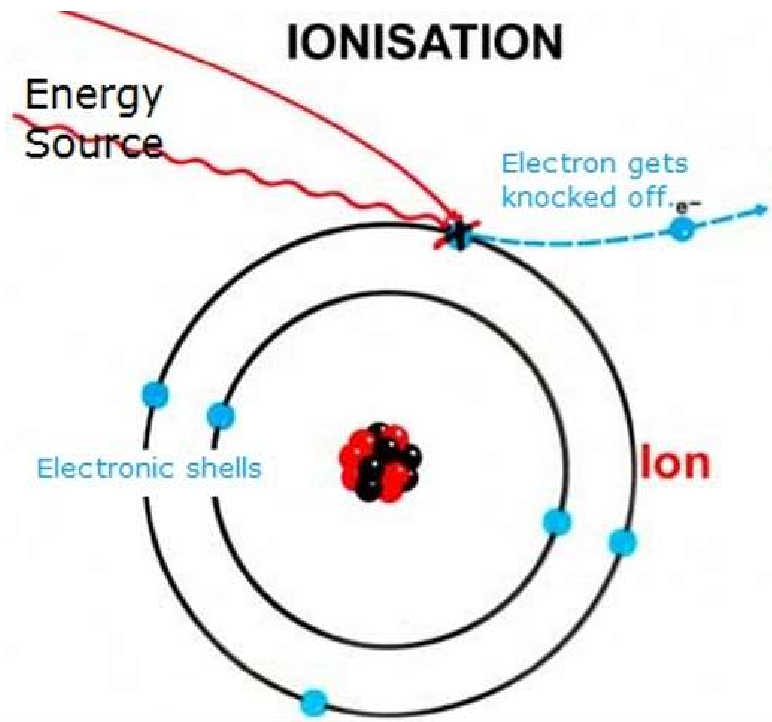
# Cathode Rays in Crooke's Tubes (discharge tubes)

- Inner shell electron removed - release of photon (light and ion formed)
- Valence shell electron removed - ion formed



Glow discharge in a low-pressure tube caused by electric current.



# Low pressure discharge tubes

**What is happening**
When a high voltage is placed across two electrodes in the gas, the electrons are accelerated in the electric field between the electrodes. If the mean free path of the electrons is long enough that over that distance they acquire enough energy, they will ionise a gas molecule. This in turn releases more electrons, which then ionise more gas molecules.

The ions thus formed can also eject electrons when they collide with the negative electrode (the cathode). The various collisions among electrons, ions and neutral gas molecules results in breakdown, and a current is sustained between the cathode and the anode of the discharge tube.

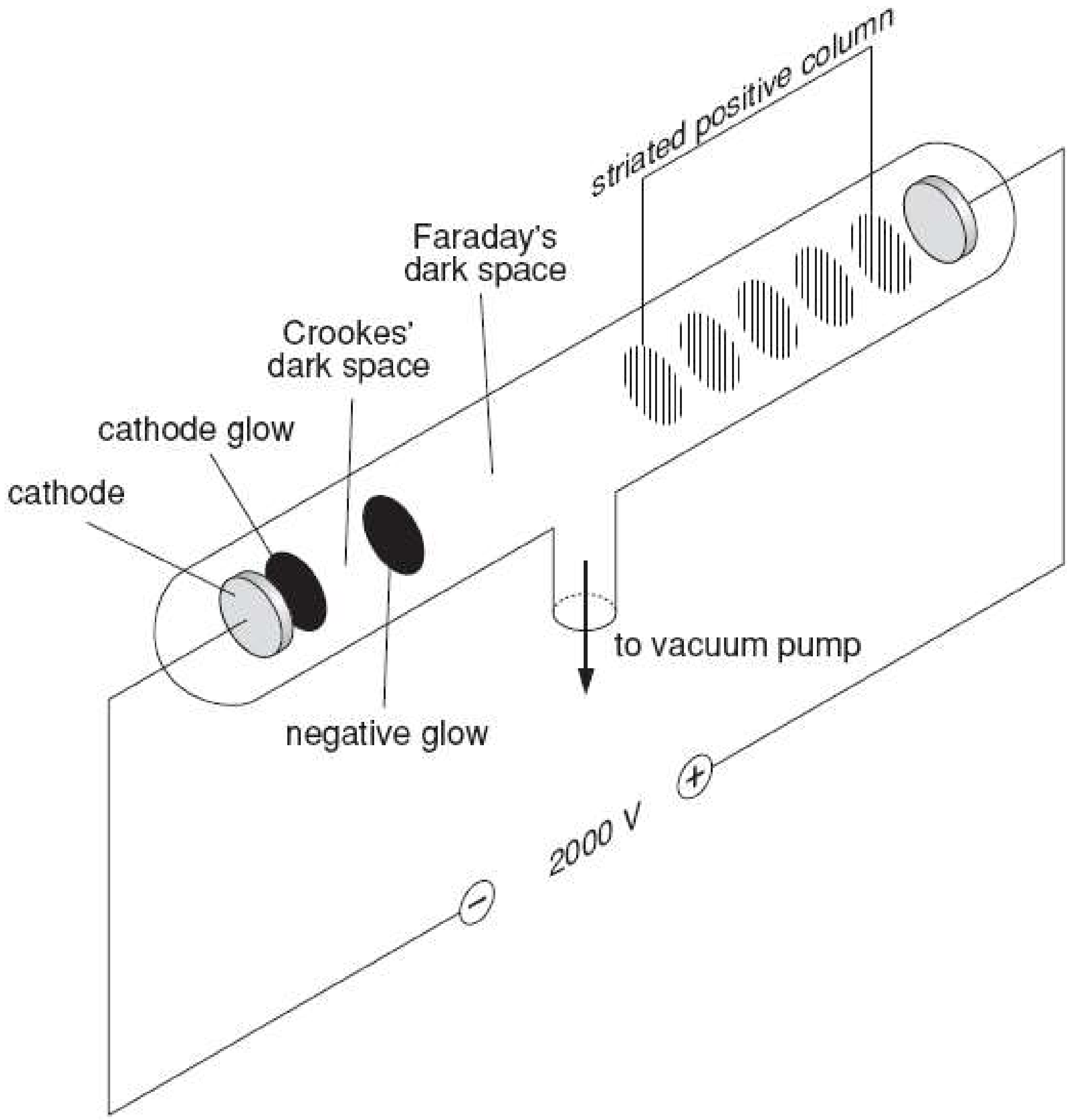
The glowing regions are black or striped in the image on the left. These regions occur as excited electrons emit photons as they move to the lower energy state.

The “dark spaces” in the images are white in this illustration. These regions are where the electrons are absorbing energy.

The striations are because:

- ionisation of the gas occurs producing light
- the electrons now have lost energy so they cannot produce ionisation
- the electrons next speed up
- ionisation of the gas occurs once again producing light.

# Discharge tubes




The “dark spaces” in the images are white in this illustration.

The glowing regions are black or striped

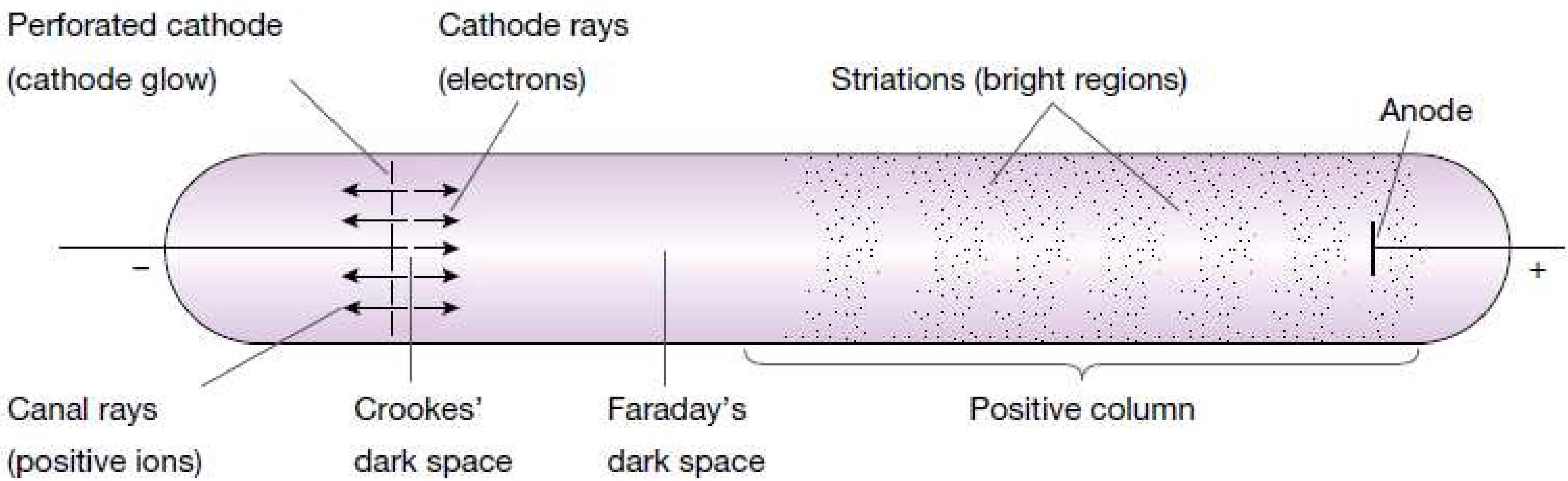
# Discharge tube interactions

1. Ionisation - electron has enough energy to remove a valence electron
2. Recombination - electron hits an ion and recombines to form a neutral atom
3. Light emission only (de-excitation)
4. Ionisation and light emission - electron has enough energy to remove an inner shell electron of a gas atom. An electron at a higher shell drops to a lower shell and releases extra energy as a photon
5. The positive ions strike the cathode and there is light emission (cathode glow)
6. Electrons strike the anode - light emission
7. Electron misses anode, hits glass and Si in glass emits light (green)

# Discharge tube processes

- Low energy collision – heat
- Higher energy collision – gas atom has electron excited - de-excited electron emits light
- Electron is removed from gas atom – ionisation
- Electron-ion recombination
- Electrons collide with the anode producing heat & light
- Electron collides with glass just past anode producing heat & light
- Ions collide with the cathode producing heat & light
- Ions collide with glass just past the cathode

# Dark and Light Patches in Discharge Tubes




- The first dark space occurs as there in not enough energy in the electron just starting near the cathode.
- When electrons have enough energy to interact with a gas atom, they release some of their energy which is emitted as light. Electrons released by the ionisation of gas atoms are still in the field so they accelerate again. Once they get enough energy, they interacts again with other gas atoms/ions and emits light, and so on.

# Difference in light and dark patches with varying pressure

Observations vary as the pressure in the discharge tube changes:

| | |
|---|---|
| High pressure | - nothing (without high voltage across the ends of the tube) |
| | - purple streamer |
| | - pinky orange |
| | - light and dark |
| | - light and dark spread further apart |
| Low pressure | - very little light, green glow just past anode |

# Difference in light and dark patches with varying pressure

Why?

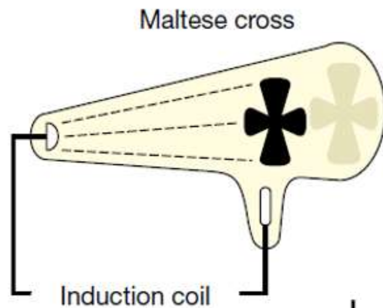
- Mean free path - The average distance between particles.
- As pressure decreases (i.e. there are less gas molecules in the tube) the particles are further apart.
- At high pressures the electrons do not gain enough energy before hitting a gas molecule (at high pressures, there are more gas molecules in the tube). The electrons are likely to hit one before travelling a long distance, hence they will hit with low energy.
- As pressure decreases, it means the free path for electrons increases. Thus more light can be emitted (as KE can increase).
- However at very low pressures there are fewer gas molecules to collide with and the electrons can travel the tube without colliding with one. Hence the light patches disappear and the glass behind the anode glows as the electrons hit the glass which excites the atoms of the glass.

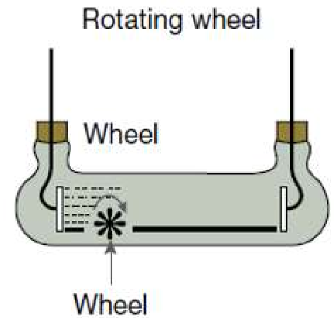
# Crooke’s tubes

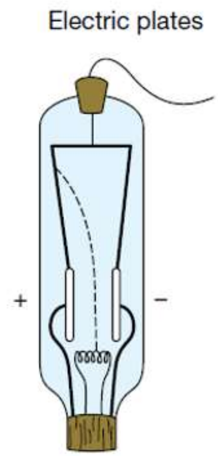
- The next few slides depict a variety of cathode ray tubes designed to elucidate the properties of cathode rays

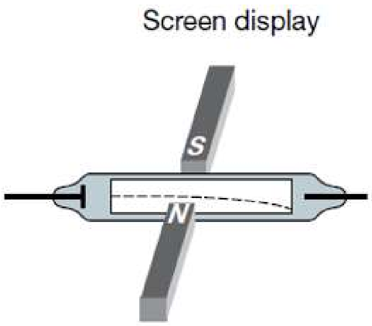
# Cathode Rays Tube – Early Experiments

- The result of the Maltese cross shows that cathode rays travel in straight lines hence casting a sharp shadow of the cross on fluorescing glass.
- The Crookes Paddle Wheel tube experiment shows that cathode rays consist of particles with mass that have momentum and the kinetic energy of these particles indirectly leads to movement of the paddle wheel.
- When two electrically charged plates were place above and below the cathode ray tube, the beam deflected towards the positive plate suggesting that cathode rays were negatively charged.
- Similarly, when magnetic field was applied perpendicularly to the direction of beam, the beam deflected in the direction which suggested that it is negatively charged.

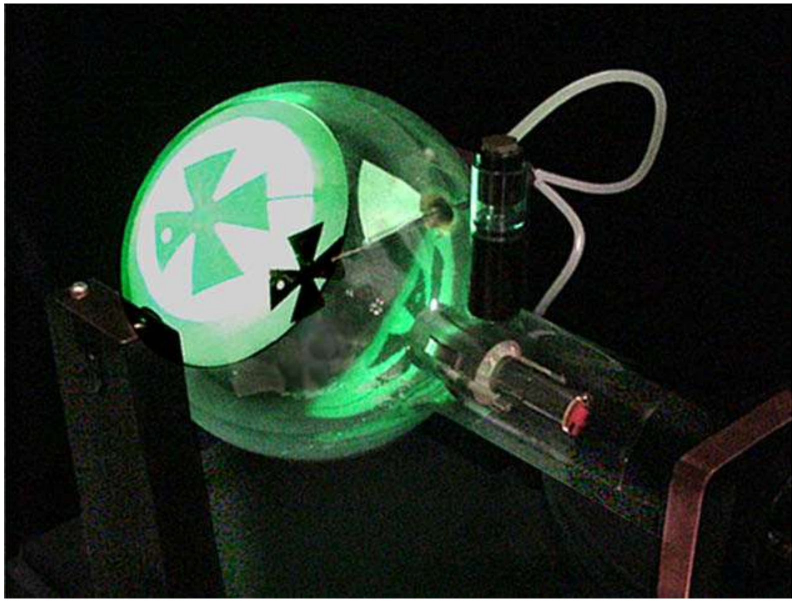


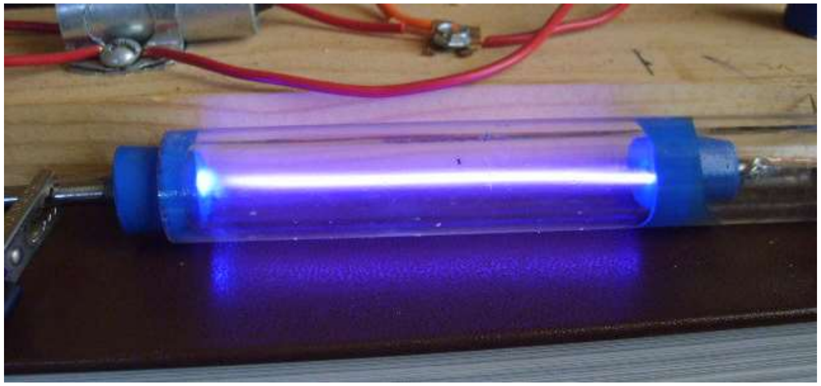



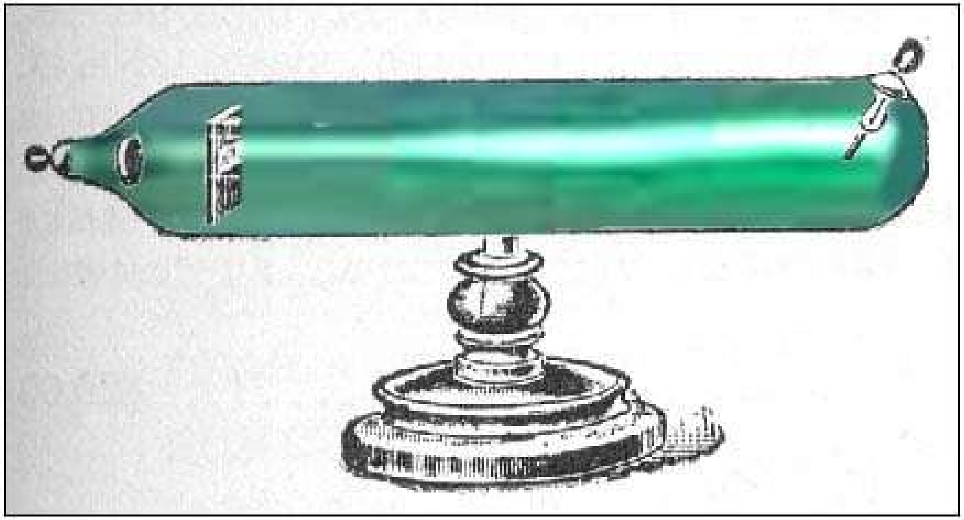
# Cathode Rays travel in straight lines



http://www.phys.unt.edu/%7Eklittler/demo_room/e&m_demos/cathode_ray_tube.JPG



http://www.primeline-america.com/tube/crt5.jpg



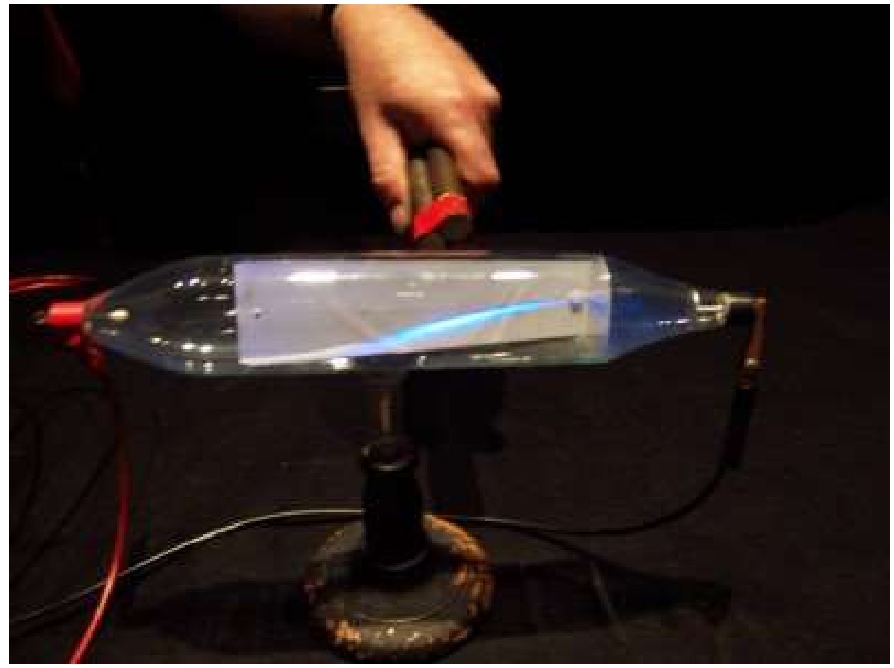
http://www.astro.virginia.edu/class/oconnell/astr121/im/crookes-tube.jpg

# Cathode rays are deflected by electric fields

# Cathode rays are deflected by magnetic fields

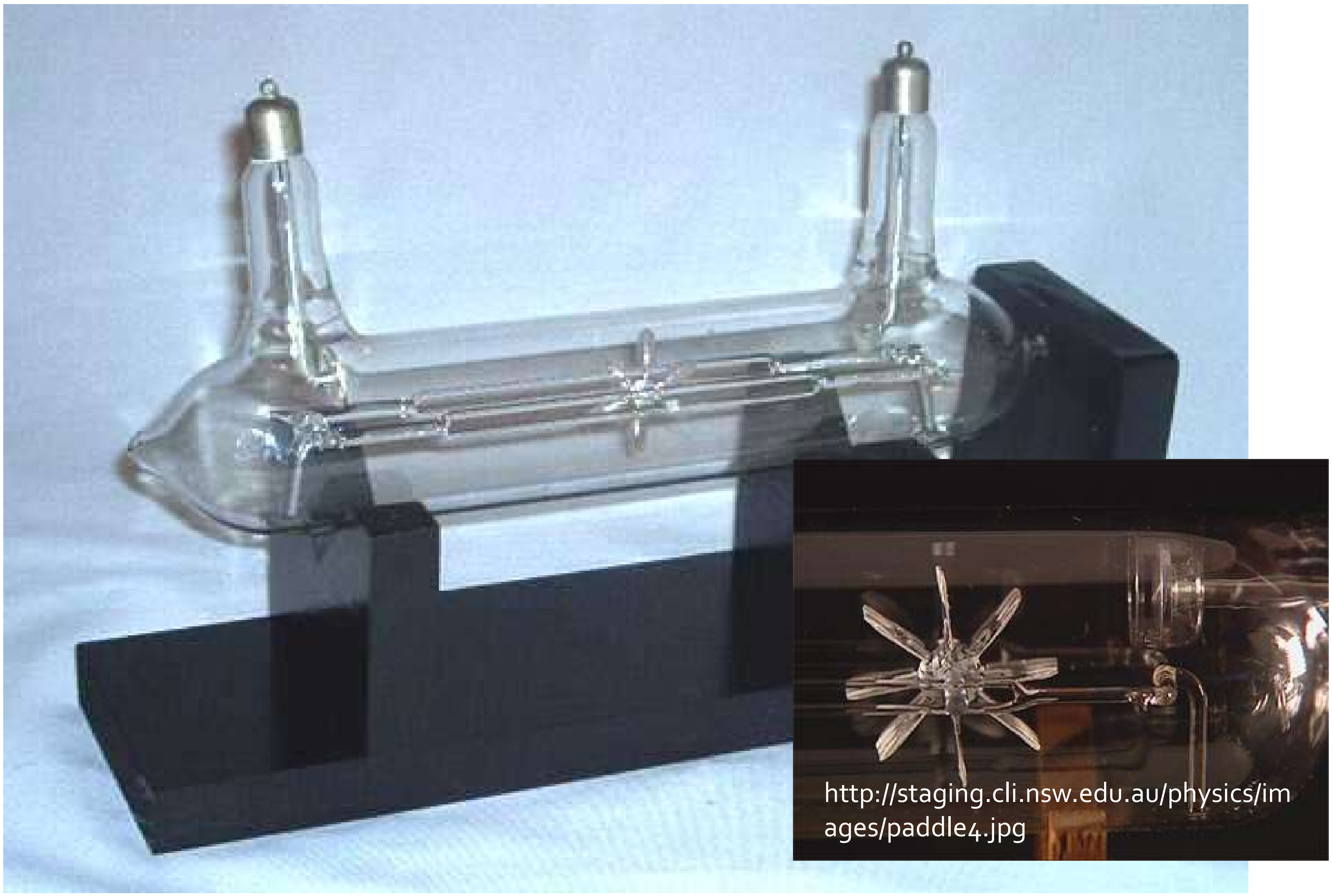
One of Thomson's original tubes (1897)

http://www.makingthemodernworld.org.uk/icons_of_invention/img/IM.1174_el.jpg



http://isites.harvard.edu/fs/docs/icb.topic182873.files/images/CathodeRayDeflection001-400x300.jpg

# Cathode rays carry momentum


http://staging.cli.nsw.edu.au/physics/images/paddle4.jpg

http://physics.kenyon.edu/EarlyApparatus/Electricity/Cathode_Ray_Tubes/Greenslade219a.JPG

# Thomson

- Interested in the nature of cathode rays
- Aimed to show that cathode rays were streams of charged particles

# Thomson’s experiment 1897

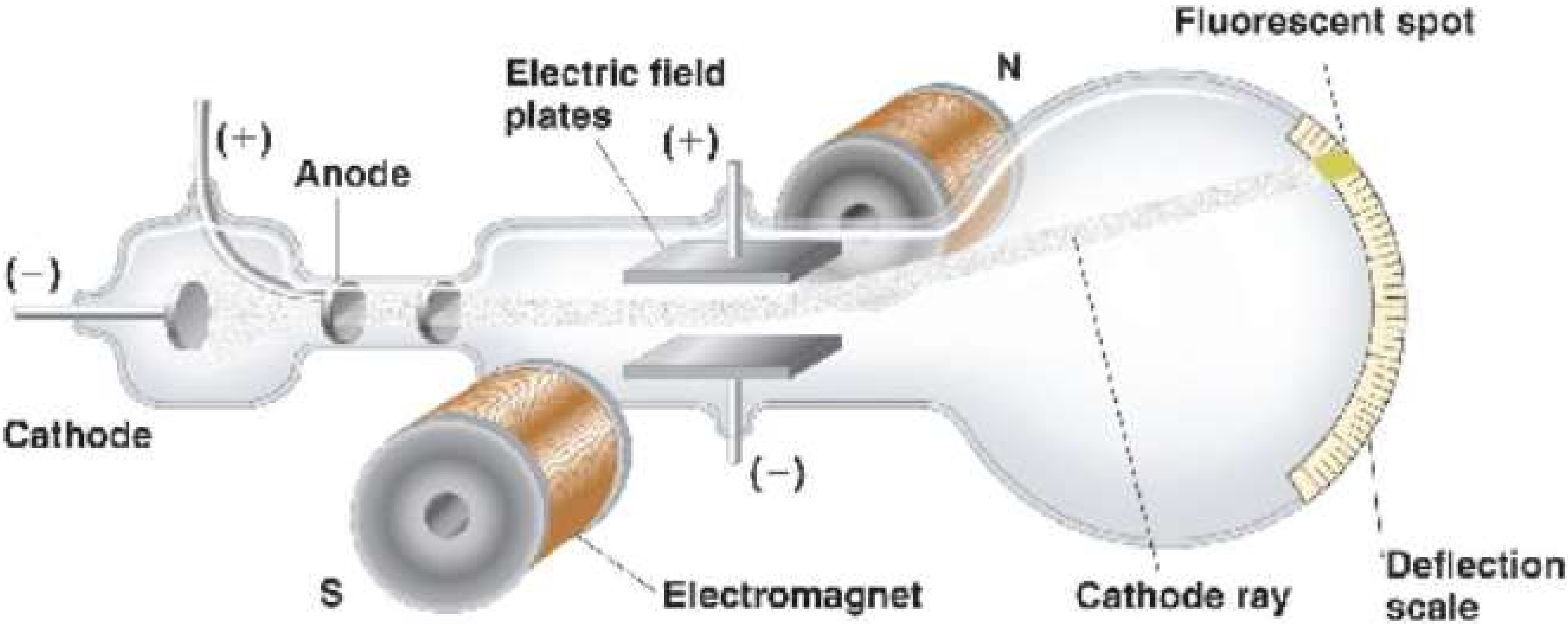



**Figure 1:** Schematic of J.J. Thomson's experiment.

# Thomson's experiment 1897

- In 1897, Thomson demonstrated that cathode ray particles are fundamental constituents of every atom. Cathode rays were renamed electrons.
- In order to measure the mass of the particle, Thomson used the degree of deflection of the beam to find the ratio of the charge of the particle to its mass, $e/m$.

https://youtu.be/_nLESblUAHY

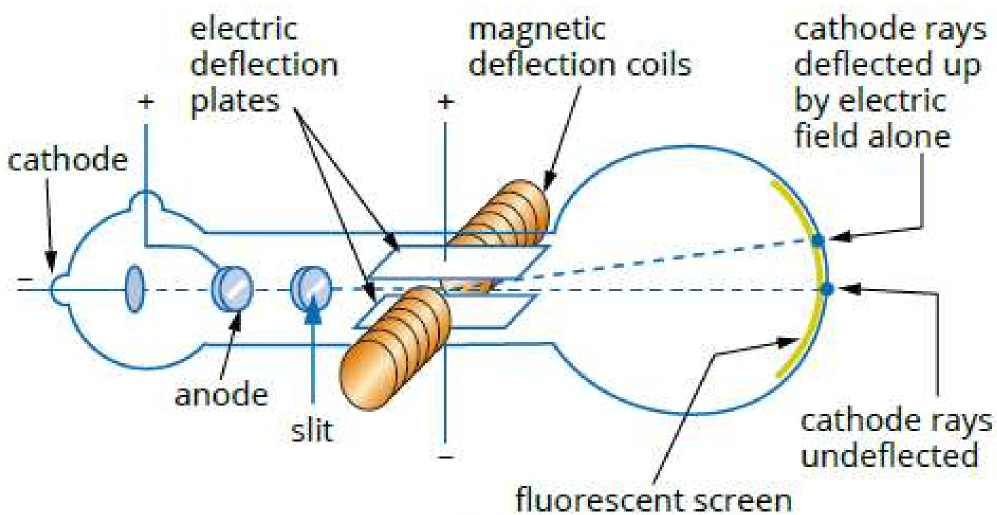
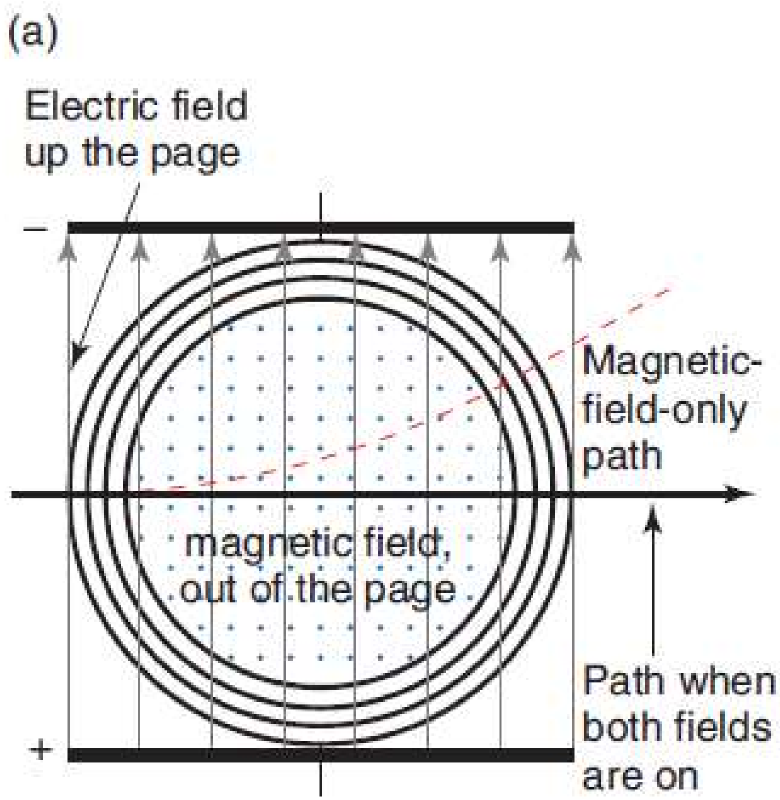
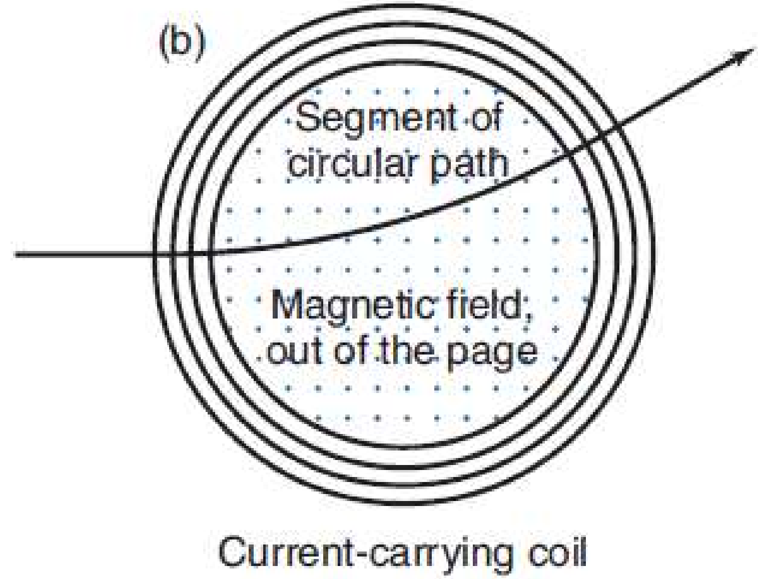



**FIGURE 14.1.4** Thomson's apparatus for finding the charge-to-mass ratio for cathode rays. Thomson used an electron gun and cathode ray tube to measure the degree of deflection of the beam.

# Thomson's experiment 1897




Here the E and B fields are in opposition




Here the E field is off and B field deflects the beam, radius of curvature is measured

# Thomson's Experiment

$$qE = qvB$$

$$v = \frac{E}{B}$$

# Thomson's experiment

magnetic force = centripetal force

$$qv\,\mathrm{B} = \frac{mv^2}{r}$$

$\theta = 90°$ so $\sin\theta = 1$

$$q\,\mathrm{B} = \frac{mv}{r}$$

$$\frac{q}{m} = \frac{v}{\mathrm{B}r}$$

# Thomson's experiment

$$v = \frac{E}{B},$$

*so*

$$\frac{q}{m} = \frac{E}{B^2 r}$$

# Motion of a Charged Particle

To calculate the speed of an electron travelling through an electric field,

- Force on a charged particle F = qE
- Force to accelerate a charged particle F = ma

$$ma = qE$$

$$ma = \frac{qV}{d} \qquad (\text{since } E = \frac{V}{d})$$

$$a = \frac{qV}{md}$$

$$v^2 = u^2 + 2as \quad (u=0)$$

$$v^2 = \frac{2qV}{m} \ (\text{since } d = s)$$

$$mv^2 = 2qV$$

$$\frac{1}{2}mv^2 = qV$$

$$KE = W$$

**MOTION OF A CHARGED PARTICLE**

A 500.0 V electrical field is applied to an electron that is initially at rest.

**a** Calculate the final speed of the electron.

$q = 1.602 \times 10^{-19}$ C
$V = 500.0$ V
$m = 9.109 \times 10^{-31}$ kg
$u = 0$ m s$^{-1}$
$v = ?$

$$\frac{1}{2}mv^2 = qV$$

$$v = \sqrt{\frac{2qV}{m}} = \sqrt{\frac{2 \times 1.602 \times 10^{-19} \times 500}{9.109 \times 10^{-31}}} = 1.326 \times 10^{7}\ \text{m s}^{-1}$$

**b** The electron enters a magnetic field of 30.0 mT and moves in a curved path. Calculate the radius of curvature of the electron's path.

$q = 1.602 \times 10^{-19}$ C
$B = 30.0$ mT $= 0.030$ T
$m = 9.109 \times 10^{-31}$ kg
$v = 1.33 \times 10^{7}$ m s$^{-1}$

$$r = \frac{mv}{qB} = \frac{9.109 \times 10^{-31} \times 1.326 \times 10^{7}}{1.602 \times 10^{-19} \times 0.030} = 0.00251 = 2.51 \times 10^{-3}\ \text{m}$$

# Thomson's Experiment – a new model of the atom!

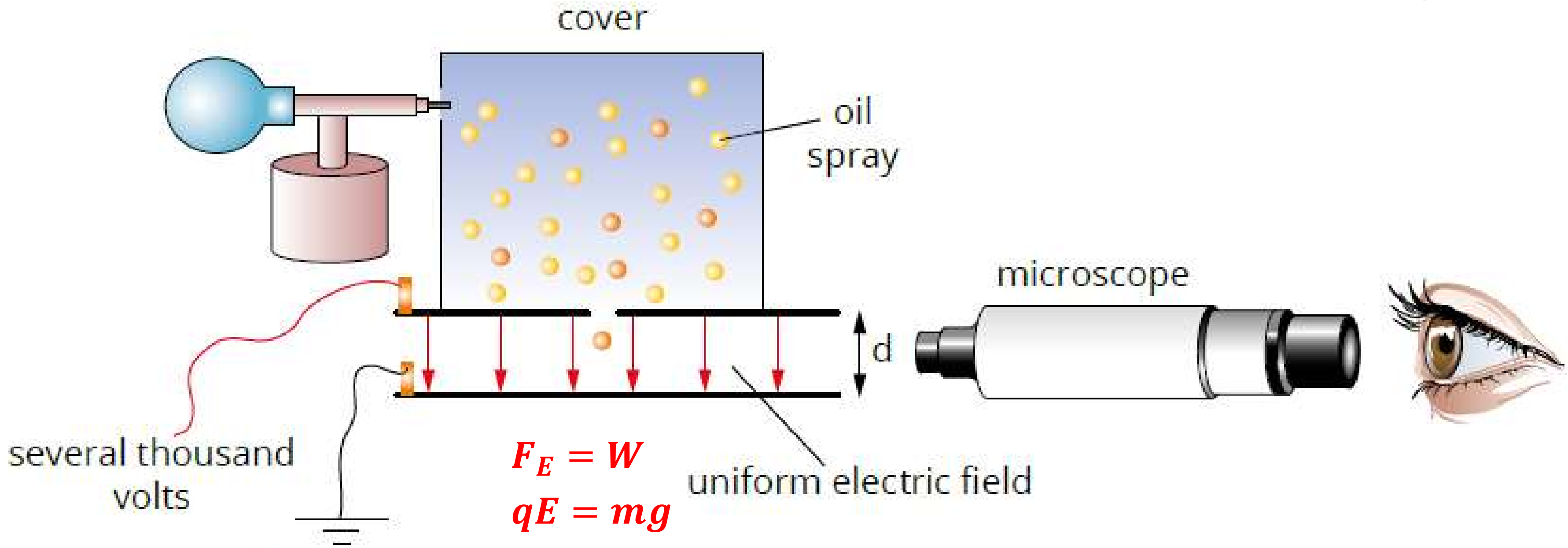
Joseph John (JJ) Thomson based his research on cathode rays. Previous attempts to bend cathode rays with an electric field had failed. Thomson suspected that the gas remaining in the tube was being turned into an electrical conductor by the cathode rays themselves. By extracting most of the gas from a tube, he found that the cathode rays did bend in an electric field after all, indicating negative charges. He used this result to measure the charge-to-mass ratio of the cathode ray particles. Thomson built a cathode ray tube with charged parallel plates and Helmholtz coils. By creating perpendicular electric and magnetic fields, he produced opposing forces on the cathode rays.

# Milikan's Oil Drop Experiment

- When a spray of oil drops was introduced between two metal plates to which an electrical potential was applied, the charged drops became suspended between them. The drop must have been in equilibrium – the electrostatic force balanced with the gravitational force.
- Some drops became charged due to friction from the spray device, however the drops could be charged to higher levels by irradiating the air with X-rays, therefore a weaker electrical field would be needed to suspend the same sized drop.
- Milikan found that the charge on a drop was always a multiple of $1.6 \times 10^{-19}$ C.
- J.J. Thomson combined his experimental result of charge-to mass ratio with the charge of an electron to calculate the mass of an electron, $m_e = 9.109 \times 10^{-31}$ kg.

# Milikan's Oil Drop Experiment

https://youtu.be/UFiPWvo3f6g




$$F_E = W$$
$$qE = mg$$

**FIGURE 14.1.5** Schematic of Millikan's experiment. As the charged drops enter the electric field, the upwards electrostatic force balances out the downwards weight force due to gravity.

# Millikan’s experiment 1906

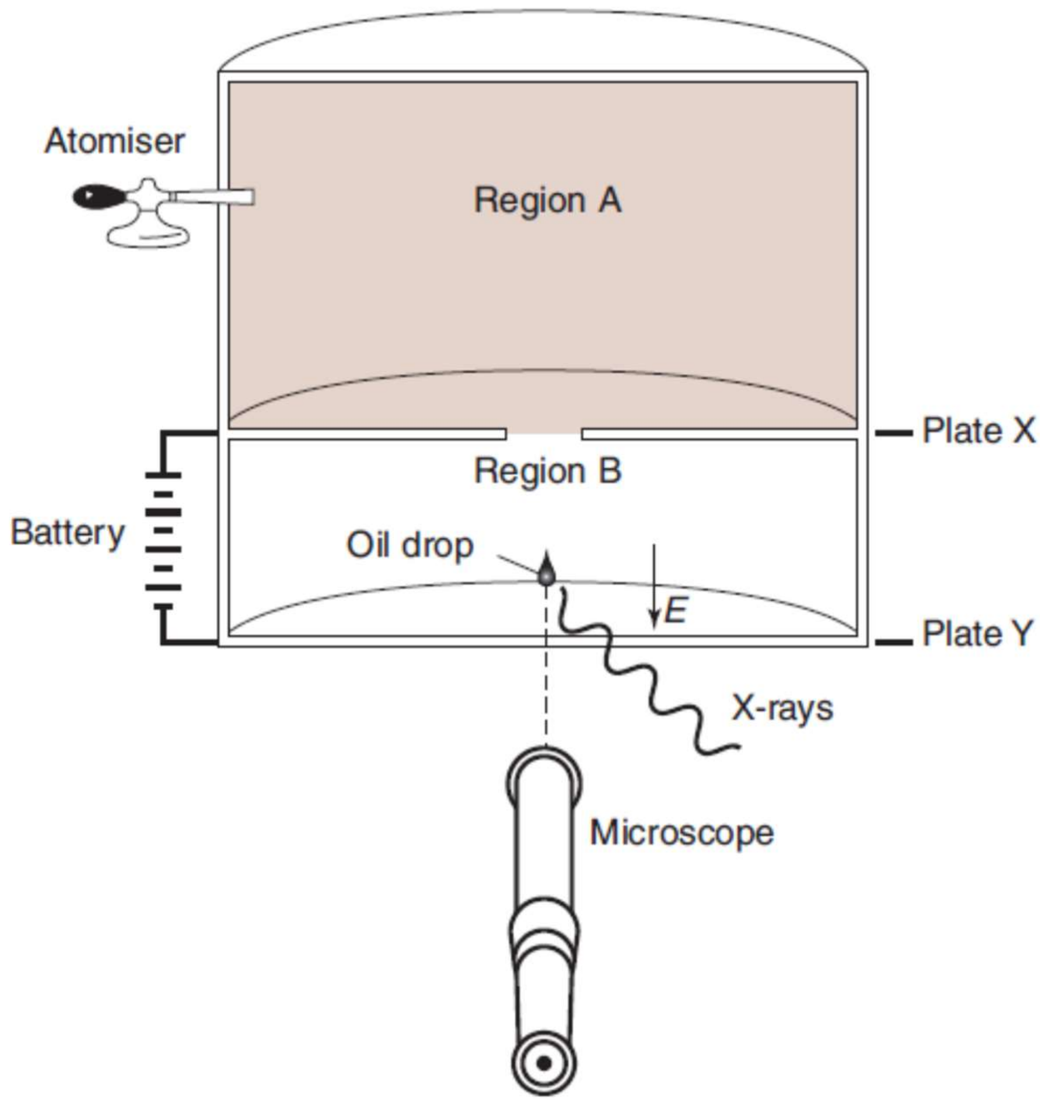
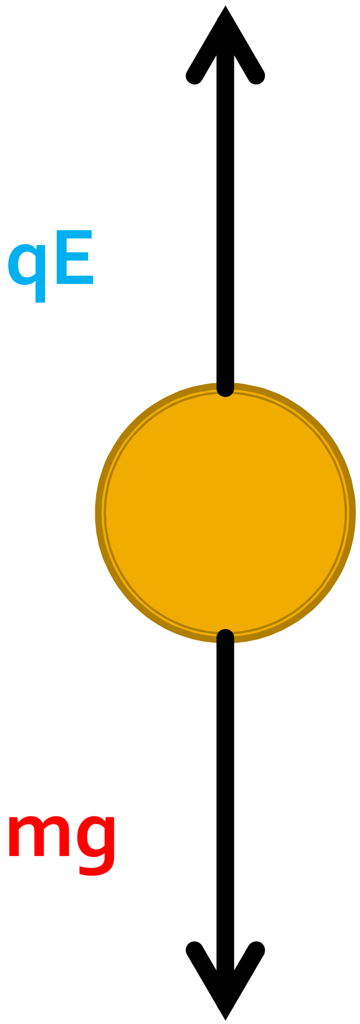



**Figure 10.11** *Apparatus for Millikan’s oil drop experiment*

When the droplet is suspended, the forces on it are equal and sum to zero




Weight force Electric field force

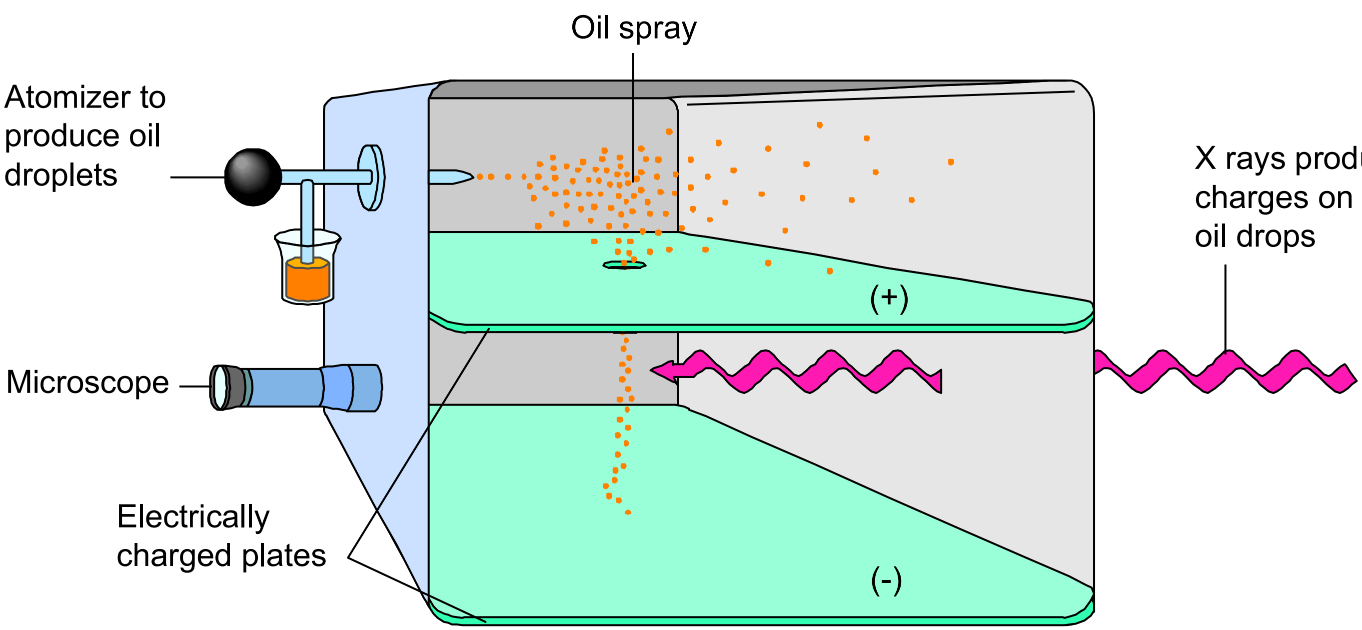
$$mg = q\mathbf{E}$$

$$q = \frac{mg}{\mathbf{E}}$$

# Charge comes in packets

- After many experiments Millikan found that the charge came in units of $1.6 \times 10^{-19}$ Coulombs.

# Milikan's Oil Drop Experiment



# New subatomic particle: the electron

- When Millikan in 1906 determined that the smallest charge was $1.6 \times 10^{-19}$ C, Thomson's work enabled calculation of the mass of the particles in cathode rays: $9.11 \times 10^{-31}$ kg.

# Atomic Model – J.J. Thomson

- Thomson knew that atoms were electrically neutral.
- In 1904 he proposed the plum pudding model of an atom which consisted of a diffuse of positive charges with negatively charged particles floating within.
- In the same year, Hantaro Nagaoka at the University of Tokyo proposed the Saturnian model in which the negative charged particles orbited around the outside of a positively charged centre.

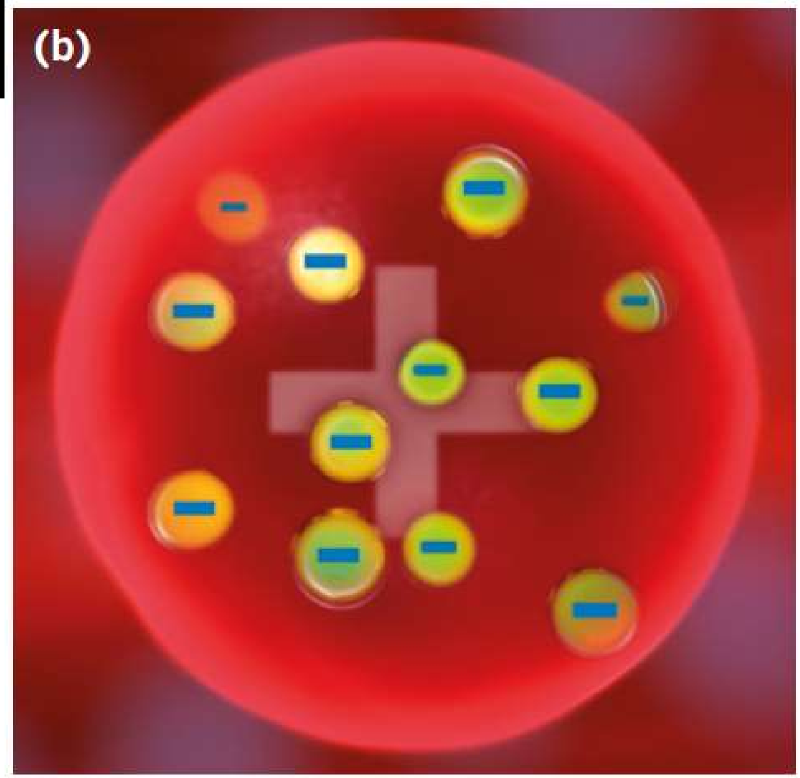
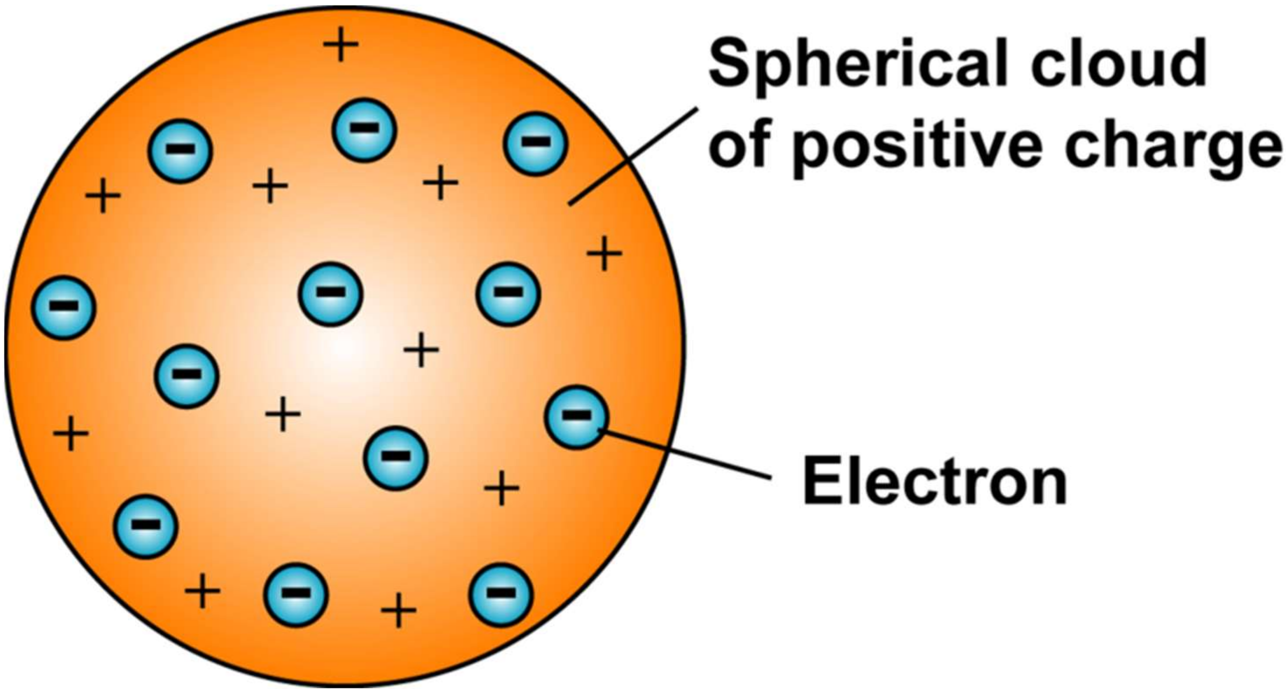



**FIGURE 14.1.6** (a) The archaic dessert, the plum pudding. (b) Thomson's atomic model. Discrete elections are distributed in a diffuse, positively charged space. This model met with the observations, although the nature of the positive-charged part of the atom remained poorly defined.

# Thomson model 1904



# Thomson summary

**STRENGTHS**

Explains:

- Why atoms are electrically neutral
- Predicts ions
- Cathode rays

**WEAKNESSES**

Does not explain:

- Atomic stability, radioactivity, atomic size, isotopes, atomic spectra, shapes of molecules, scattering of alpha particles by foils, electron diffraction
- allotropes of elements e.g. carbon as diamond or graphite
- How molecules form – no bonding mechanism
- How atoms interact – no forces
- gravity
- Masses of atoms
- The particle zoo (neutrinos etc)
- Structure of periodic table

[redacted]

## KEY QUESTIONS

*To answer these questions use* $q_e = -1.602 \times 10^{-19}$ *C and* $m_e = 1.109 \times 10^{-31}$ *kg.*

**1** An electron-gun assembly emits electrons with energies of 10.0 keV.

**a** Calculate the magnitude of the predicted exit velocity of the electrons. (Ignore any effects of relativity.)

**b** Upon exiting the electron-gun assembly, the electrons enter a uniform magnetic field of 1.50 mT oriented perpendicular to their motion. Calculate the predicted radius of the electron beam.

**2** A muon, a particle of mass $1.88 \times 10^{-28}$ kg and the same charge as an electron, encounters the same 10.0 keV accelerating voltage and 1.50 mT magnetic field as in Question 1. What is its exit velocity and the radius of curvature of its path?

**3** An earlier version of Millikan's oil-drop experiment used water. Suggest one reason why oil was preferred.

**4** Research online or in other appropriate sources in order to complete the following table:

| Atomic model | Description |
|---|---|
| solid-ball model | |
| plum-pudding model | |
| nuclear model | |
| planetary model | |

[redacted]

**1** **a** $v = \sqrt{\frac{2qV}{m}}$

$= \sqrt{\frac{2 \times 1.602 \times 10^{-19} \times 10 \times 10^{3}}{9.109 \times 10^{-31}}}$

$= 5.93 \times 10^{7}\,\mathrm{m\,s^{-1}}$

**b** $r = \frac{mv}{qB}$

$= \frac{9.109 \times 10^{-31} \times 5.93 \times 10^{7}}{1.602 \times 10^{-19} \times 1.5 \times 10^{-3}}$

$= 22.5\,\mathrm{cm}$

**3** Water is more volatile (evaporates easily) than oil, so the mass and size of the droplets change more rapidly than oil drops. (In Millikan's original experiment, the water evaporated in around two seconds!)

**4**

| **Atomic model** | **Description** |
|---|---|
| solid-ball model | An indivisible ball. Where the name atom first appeared as it was referred to as *atomos*, meaning indivisible. |
| plum pudding model | From Thomson's experiments with electrons, he proposed the plum pudding model in 1904. The atom in this model is a ball of positive charge with negative charges embedded within it. |
| nuclear model | The majority of the mass of an atom in this model is in a small positive nucleus which is surrounded by negative electrons. |
| planetary model | The electrons in this model orbit the positive nucleus in specific pathways, like planets orbiting the Sun. |

**2** $v = \sqrt{\frac{2qV}{m}}$

$= \sqrt{\frac{2 \times 1.602 \times 10^{-19} \times 10 \times 10^{3}}{1.88 \times 10^{-28}}}$

$= 4.13 \times 10^{6}\,\mathrm{m\,s^{-1}}$

$r = \frac{mv}{qB}$

$= \frac{1.88 \times 10^{-28} \times 4.13 \times 10^{6}}{1.602 \times 10^{-19} \times 1.5 \times 10^{-3}}$

$= 3.23\,\mathrm{m}$

The muon is slower as there is a greater mass to accelerate. And with more mass for the same charge as the electron, the turning radius is greater.

## Sample problem 8.3

Two metal plates separated by 1.00 cm have a potential difference of 4.00 kV applied across them. A uniform magnetic field of size 20.0 mT is applied perpendicular to the plates so that an electron moving perpendicular to both fields experiences no net force.

(a) Show in a diagram the relative orientation of the electric field, the magnetic field, and the direction of the electron.

(b) Calculate the speed of the electron.

(c) What is the radius of the electron orbit when the electric field is removed?

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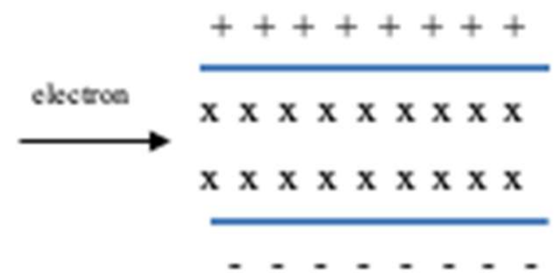
(b) Calculate the speed of the electron.

(c) What is the radius of the electron orbit when the electric field is removed?

**Solution:**

(a) One possible arrangement is that the electric field is down the page, the magnetic field is into the page and the electron travels from left to right in the plane of the page. This with the appropriate values of $E$ and $B$ can produce no net force, that is the electron will travel in a straight line.




(b) $E = \frac{V}{d}$ = 4.00 x 10$^3$/1.00 x 10$^{-2}$ = 4.00 x 10$^5$ V m$^{-1}$. The speed of the electron is found from $v = \frac{E}{B}$ = 4.00 x 10$^5$/20 x 10$^{-3}$ = 2.0 x 10$^7$ m s$^{-1}$.

(c) $qvB = \frac{mv^2}{r}$ or $r = \frac{mv}{qB} = \frac{9.109 \times 10^{-31} \times 2.0 \times 10^7}{1.602 \times 10^{-19} \times 20 \times 10^{-3}}$ = 5.69 x 10$^{-3}$ m.