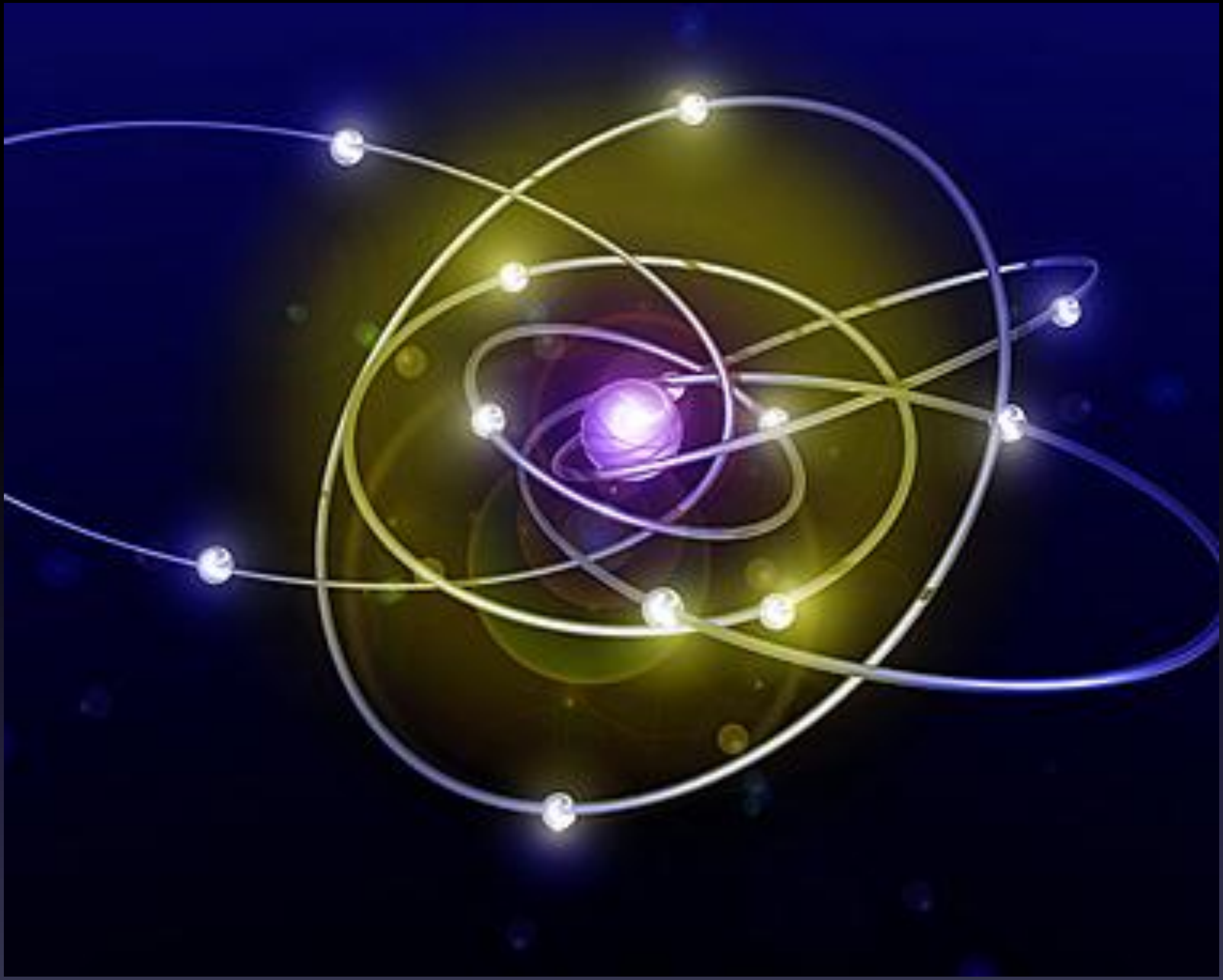
2.3 Modern Physics

3 Credits, Internal

Topic Outline

Section
Models of the Atom
Radioactive Decay
Fission and Fusion
Nuclear Power



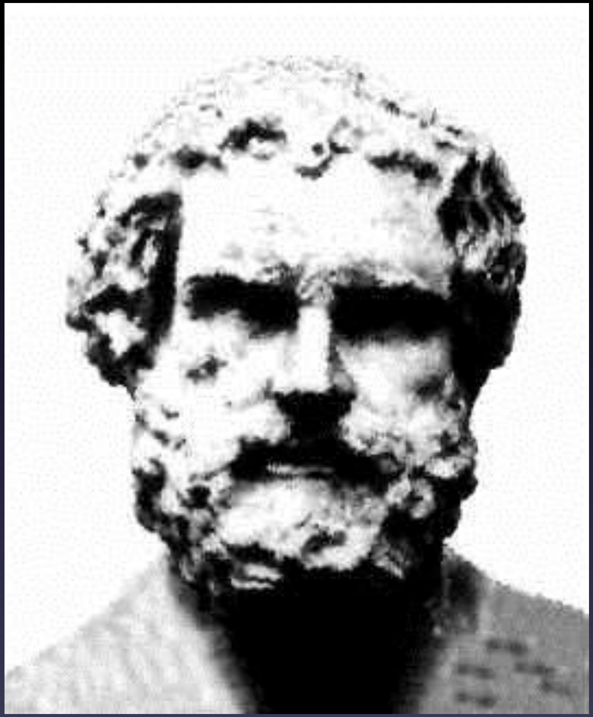
Models of the Atom

Models of the Atom

Person and Dates	Model of the Atom	Diagram	Evidence
Democritus			
John Dalton			
Sir JJ Thomson			
Sir Ernest Rutherford			
Niels Bohr			

Democritus

(c.460-c.370 BC)



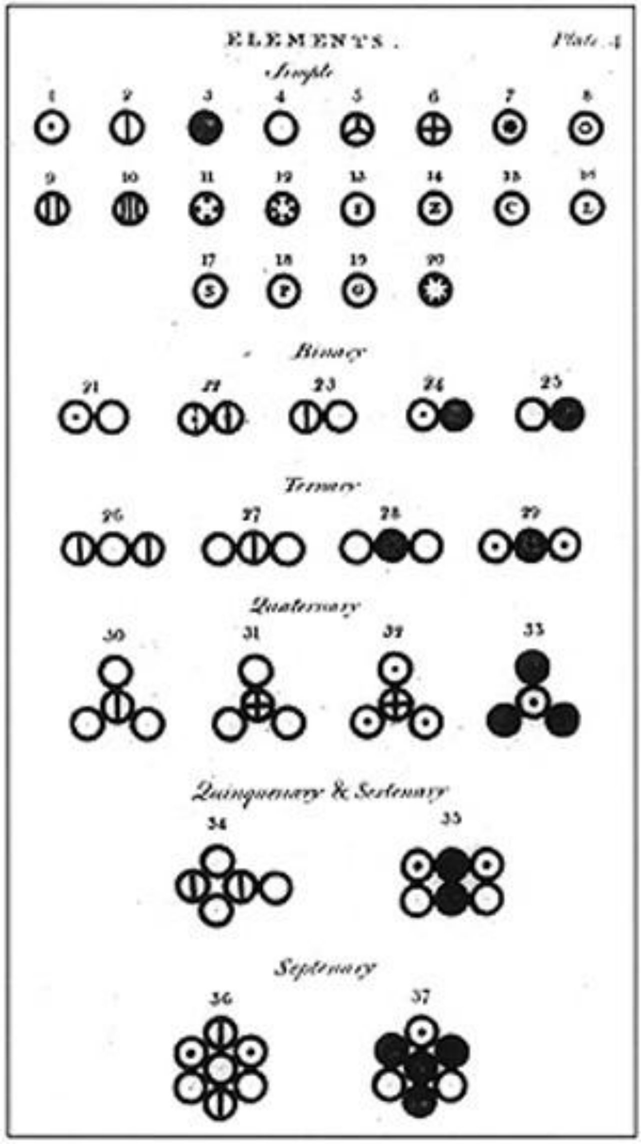
- Democritus was a philosopher in ancient Greece
- He thought that matter was made up of tiny particles too small to be divided
- The Greek word *atomos* means ‘indivisible’

John Dalton

(1766-1844)

- Dalton was an English scientist
- He developed modern atomic theory
- His model of the atom is called the ‘billiard-ball model’

Dalton’s Billiard-Ball Model



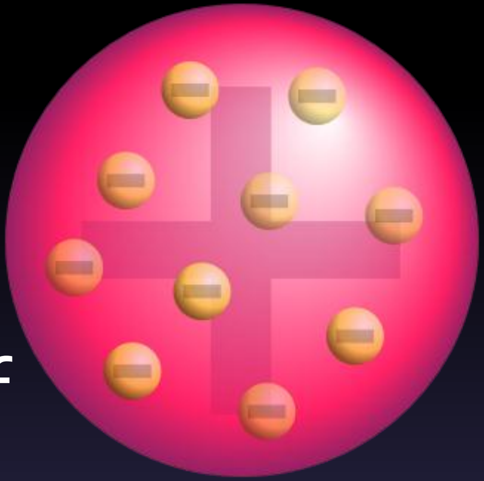
- All matter is made of tiny particles called atoms
- Atoms of the same element are identical
- Atoms can combine to form compounds
- Chemical reactions change the grouping of atoms, but not the atoms themselves

Sir J J Thomson

(1856-1940)

- Thomson was a British physicist
- He did experiments on cathode rays and discovered the electron
- In 1906, he was awarded a Nobel prize for his discovery
- His model of the atom is called the 'plum-pudding model'

Thomson’s Plum-Pudding Model



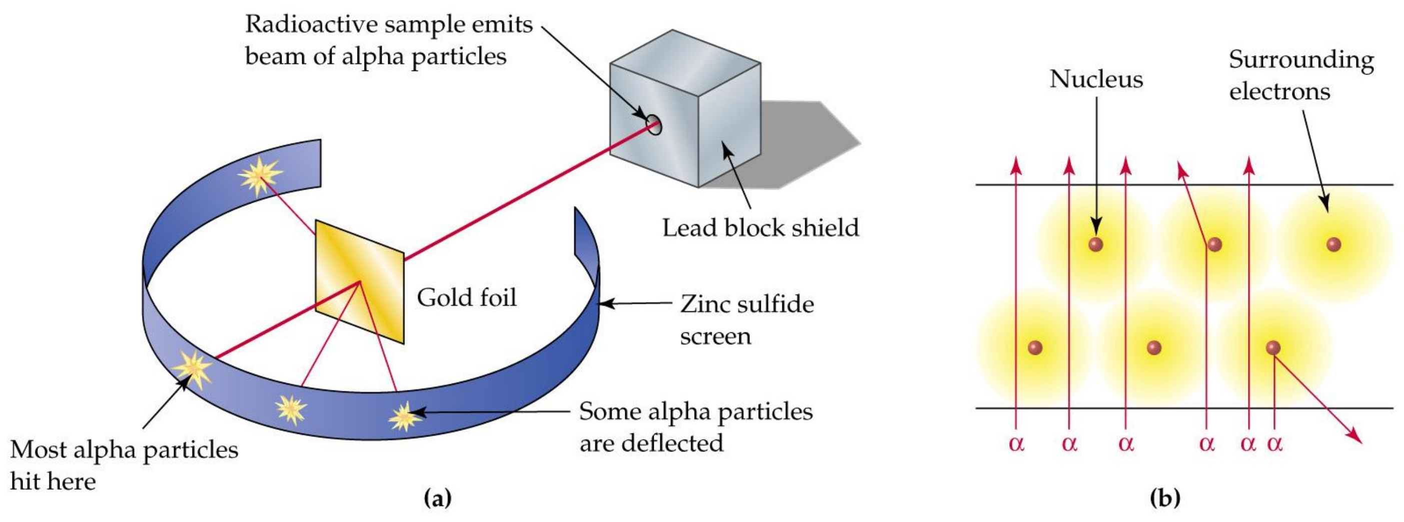
- Thomson realised that negatively charged electrons could be removed from an atom
- He proposed that atoms consist of negatively-charged electrons (the ‘plums’) embedded in a positively-charged atom (the ‘pudding’)

Sir Ernest Rutherford

(1871-1937)

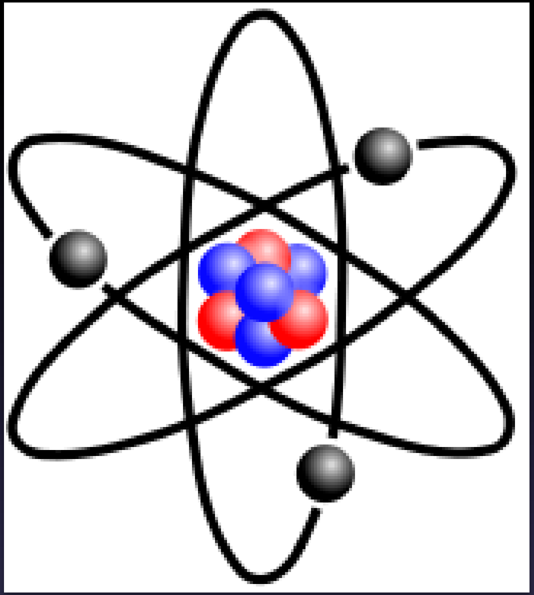
- Rutherford was a chemist from Nelson, New Zealand
- Based on the results of his gold-foil experiment, he proposed that most of the mass of an atom is concentrated in a central *nucleus*
- He won the Nobel Prize for Chemistry in 1908

Rutherford’s Gold-Foil



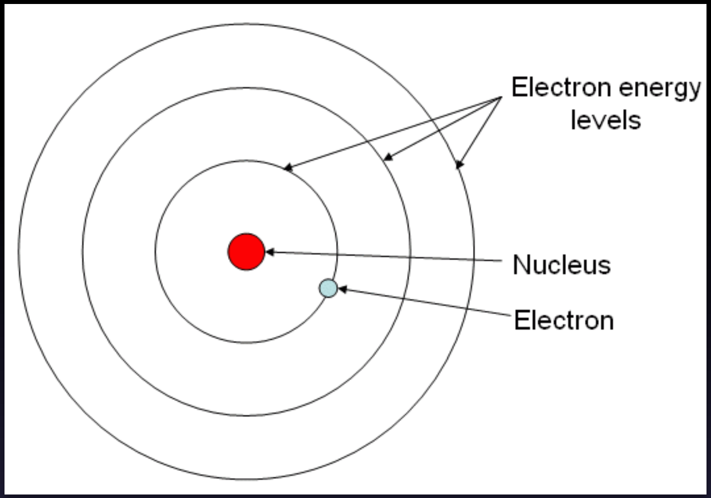
- In the famous gold-foil experiment, Rutherford’s students Geiger and Marsden fired alpha particles at a thin sheet of gold foil
- They found that some particles were deflected through large angles and some even bounced back

Rutherford's Nuclear Model



- Rutherford concluded that:
  - Most of the mas in an atom must be in a very small, positively-charged nucleus in the centre of the atoms
  - Electrons orbit around this central nucleus
  - There is a basic unit of positive charge in the nucleus, which he called the proton

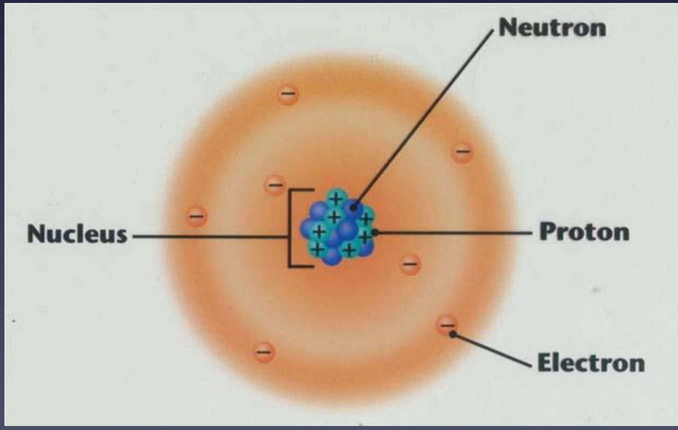
Niels Bohr (1885-1962)

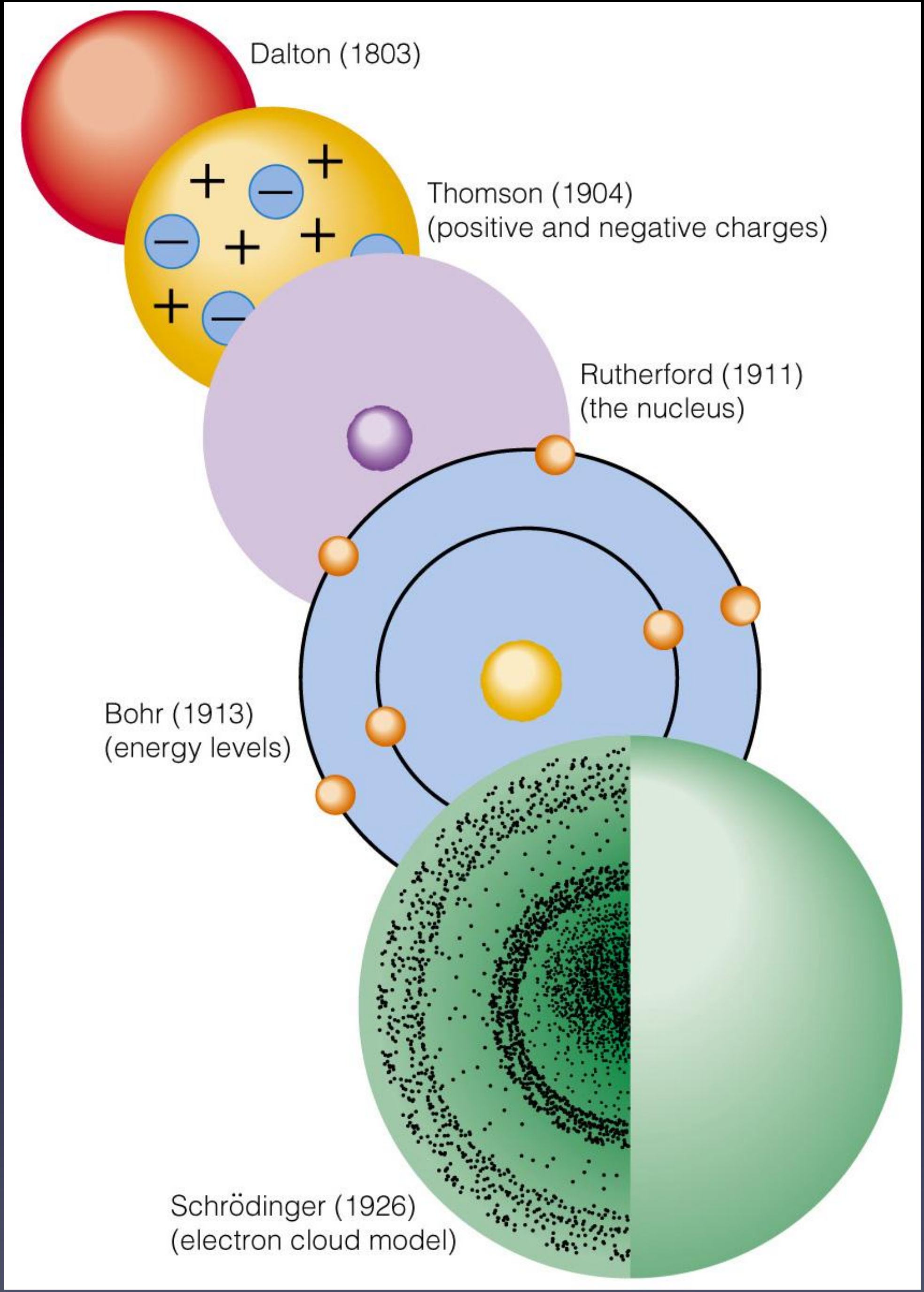


- In 1913, Bohr proposed that electrons could only occupy certain stable orbits around the nucleus
- He suggested that the *angular momentum* of the orbiting electrons is *quantised*

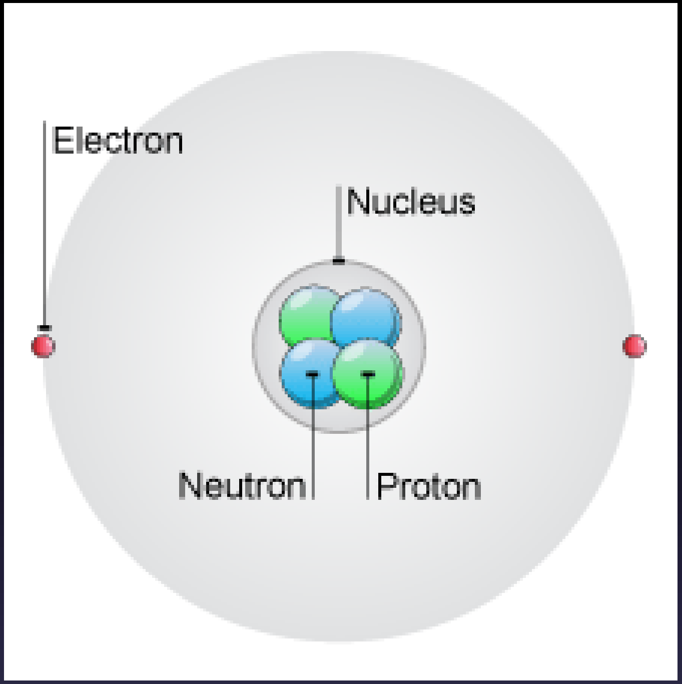
Further Developments

- **Louis de Broglie** (1892-1987) proposed that electrons can be regarded as waves
- **Sir James Chadwick** (1891-1974) discovered the **neutron**, a nuclear particle with similar mass to a proton but no electrical charge
- **Erwin Schrodinger** (1887-1961) described electrons as existing as a 'cloud' around the nucleus




Dalton (1803)
Thomson (1904)
(positive and negative charges)
Rutherford (1911)
(the nucleus)
Bohr (1913)
(energy levels)
Schrödinger (1926)
(electron cloud model)

Nuclear Model of the Atom



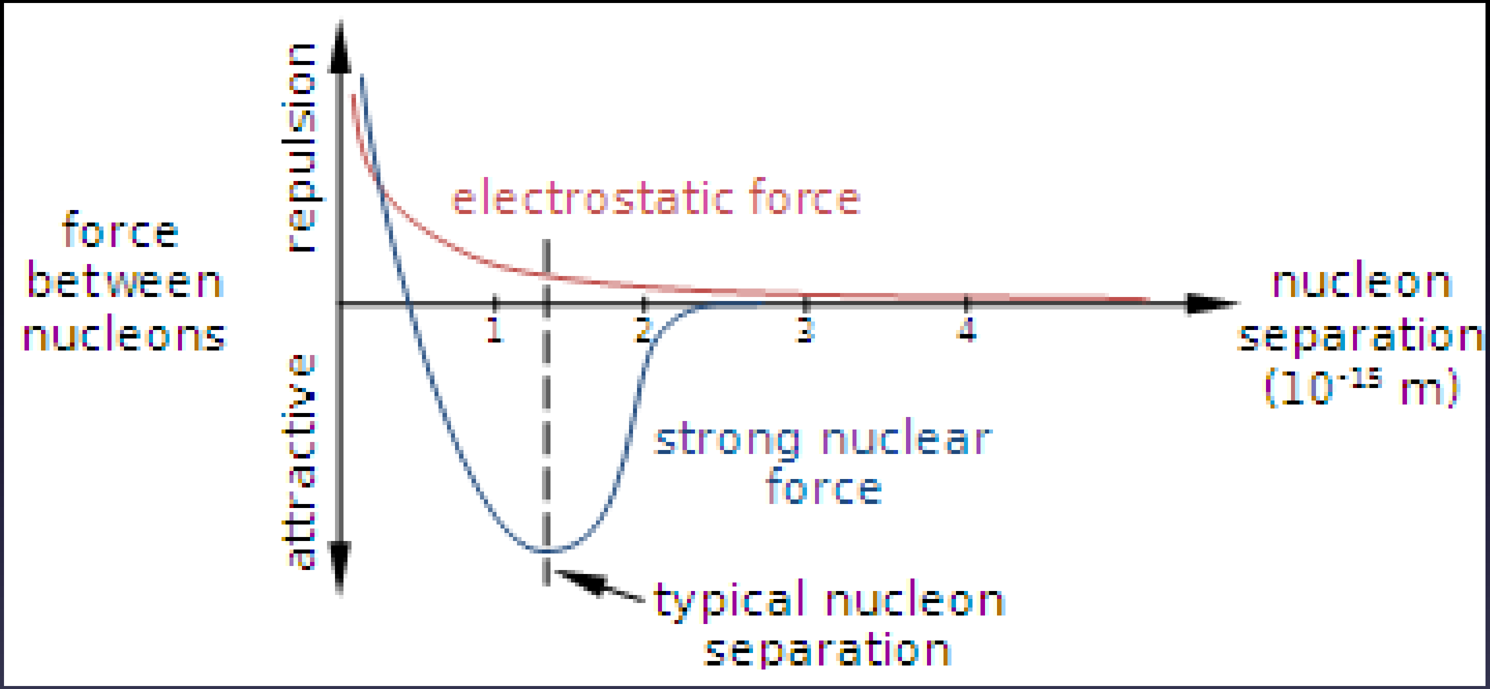
Atoms consist of:

- **Protons**
  - positively charged (+1.6 x 10^{-19} C)
  - have a mass of about 1.67 x 10^{-27} kg
  - are found in the nucleus
- **Neutrons**
  - electrically neutral
  - have a mass of about 1.67 x 10^{-27} kg
  - are found in the nucleus
- **Electrons**
  - negatively charged (-1.6 x 10^{-19} C)
  - have a mass of about 9.11 x 10^{-31} kg (about 1/2000 the mass of a proton)
  - orbit around the nucleus in particular energy levels called shells or orbitals
- Protons and neutrons are collectively called **nucleons**

Nuclear Model of the Atom

- The **electrostatic attraction** between the protons and the electrons provides the centripetal force to keep the electrons orbiting around the nucleus
- The **strong nuclear force** binds the protons and neutrons together in the nucleus
  - This force overcomes the electrostatic repulsion (Coulomb force) between the protons
  - This force is only significant over very small distances, and keeps the nucleons in a nucleus about 1.3 fm (i.e. 1.3×10^{-15} m) apart

Force Between Nucleons



Nucleon Number

- The standard way of representing an atom shows the chemical symbol (or nuclide), atomic number (or proton number) and mass number (or nucleon number)
- For example:

$${}^{23}_{11}Na$$

- This atom of sodium (Na) has an atomic number of 11 (i.e. 11 protons) and a mass number of 23 (i.e. 23 nucleons); since 23 - 11 = 12, the atom has 12 neutrons
- The generalised diagram for this is:

$${}^{A}_{Z}X$$

A = mass number (or nucleon number) = number of protons + neutrons

X = element symbol (or nuclide)

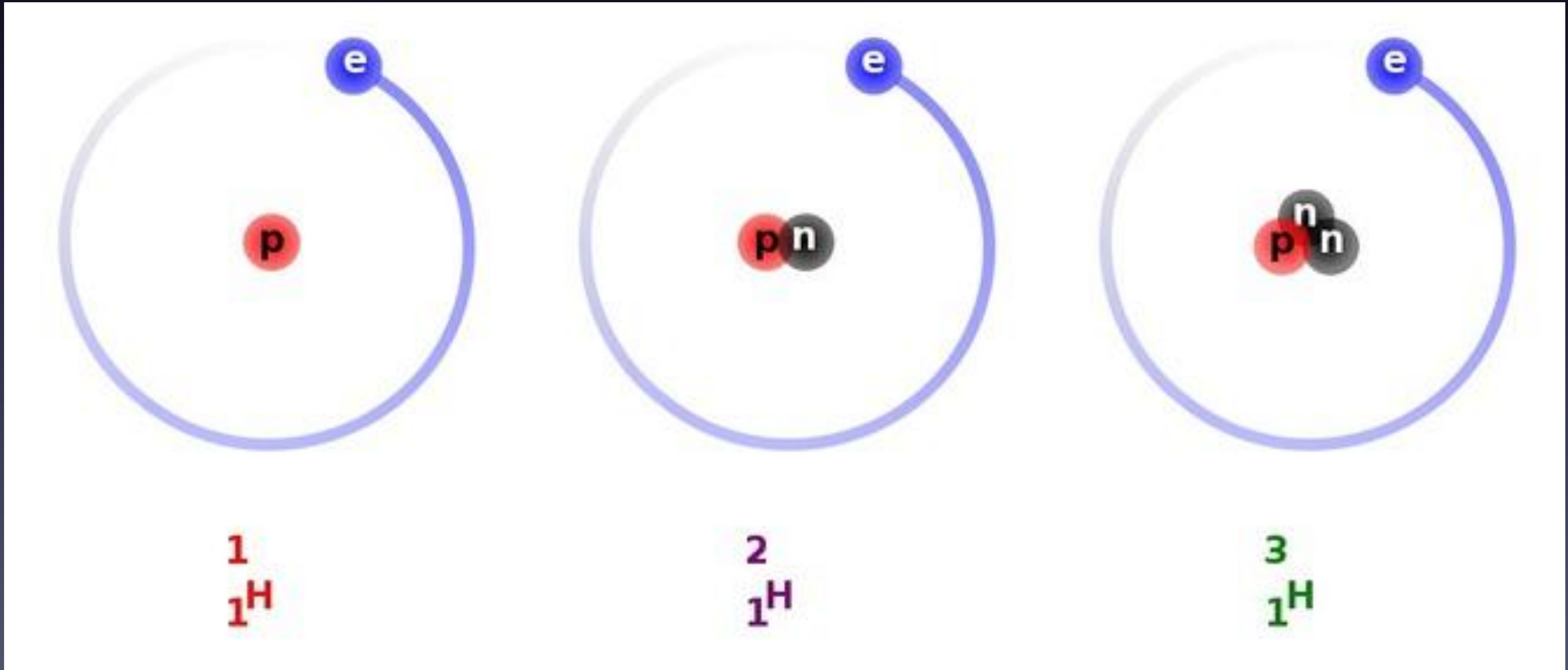
Z = atomic number (or number of protons)

Isotopes

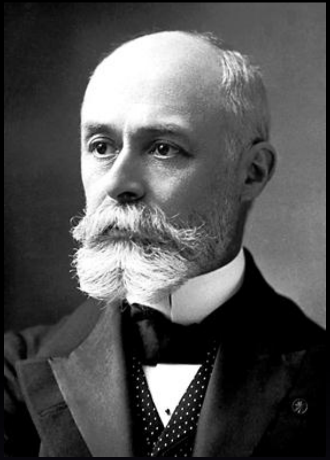
- **Isotopes** of an element have the same number of protons (the number of protons in a nucleus defines which element it is) but a different number of neutrons
- Isotopes of a given element have the same chemical properties, the same atomic number, but a different mass number

Isotopes of Hydrogen

Standard Hydrogen	Deuterium	Tritium
$^{1}_{1}H$	$^{2}_{1}H$	$^{3}_{1}H$
1 proton	1 proton + 1 neutron	1 proton + 2 neutrons



Radiation



Radioactivity

- In 1896, the Austrian physicist Henri Becquerel discovered radioactivity when studying uranium salts
- Shortly after this, Pierre and Marie Curie isolated two other radioactive elements: polonium and radium

- **Radioactive elements** are elements that spontaneously emit high-speed particles

  or high energy waves from its nucleus
- Radioactivity is a property of the nucleus of the atom and is independent of the chemical state of the atom

Radiation Summary

Type of Radiation	Nature of Radiation	Represented by	Ionising ability	Penetrating ability	Stopped by
α-particle					
β-particle					
γ-ray					

Types of Radiation

- An **α-particle** is a helium nucleus (2 protons + 2 neutrons) released at high speed from a nucleus
- An α-particle is represented by $^{4}_{2}He$

For example, decay of a uranium nucleus to form a thorium nucleus and an α-particle

$$^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He$$

Types of Radiation

- A **β-particle** is a high energy electron that is released from a nucleus.
- A β-particle is formed when a neutron splits into a proton (positive) and an electron (negative)
- A β-particle is represented by $^{0}_{-1}\beta$

For example, decay of a thorium nucleus to form a protactinium nucleus and a β-particle

$$^{234}_{90}\mathrm{Th} \rightarrow {}^{234}_{91}\mathrm{Pa} + {}^{0}_{-1}\beta + \overline{\nu}$$

- In this reaction, a neutron in the thorium nucleus splits into a proton and an electron (β-particle)

Types of Radiation

- A **positron** (${}^{0}_{+1}\beta$) is similar to a β-particle in that it has the same mass and the same magnitude of charge, but it is positive instead of negative
- A positron is the **antiparticle** of an electron
- When a positron is released from a nucleus it is also a type of β-radiation

Types of Radiation

- **γ-rays** are very high energy (short wavelength) electromagnetic waves that are released from a nuclear reaction

For example, iodine-131 going from an excited state to a lower energy state

$$^{131}_{53}\mathrm{I}^* \rightarrow {}^{131}_{53}\mathrm{I} + \gamma$$

Ionising Radiation

- α-particles, β-particles, γ-rays, cosmic rays and X-rays are all forms of **ionising radiation**; they all have the ability to interact with matter to form ions
- Ionising radiation can damage DNA, which can cause uncontrolled cell division and cancer
- Ionising radiation can also affect metabolic pathways and the functioning of cells

Properties of Radiation

α-Radiation

- α-particles are strong ionisers, and they have the ability to remove electrons from other atoms (creating ions)
- Because of this, α-particles can be very damaging to living tissue
- However, α-particles are not very penetrating, and most can be stopped by a layer of thin cardboard

Properties of Radiation

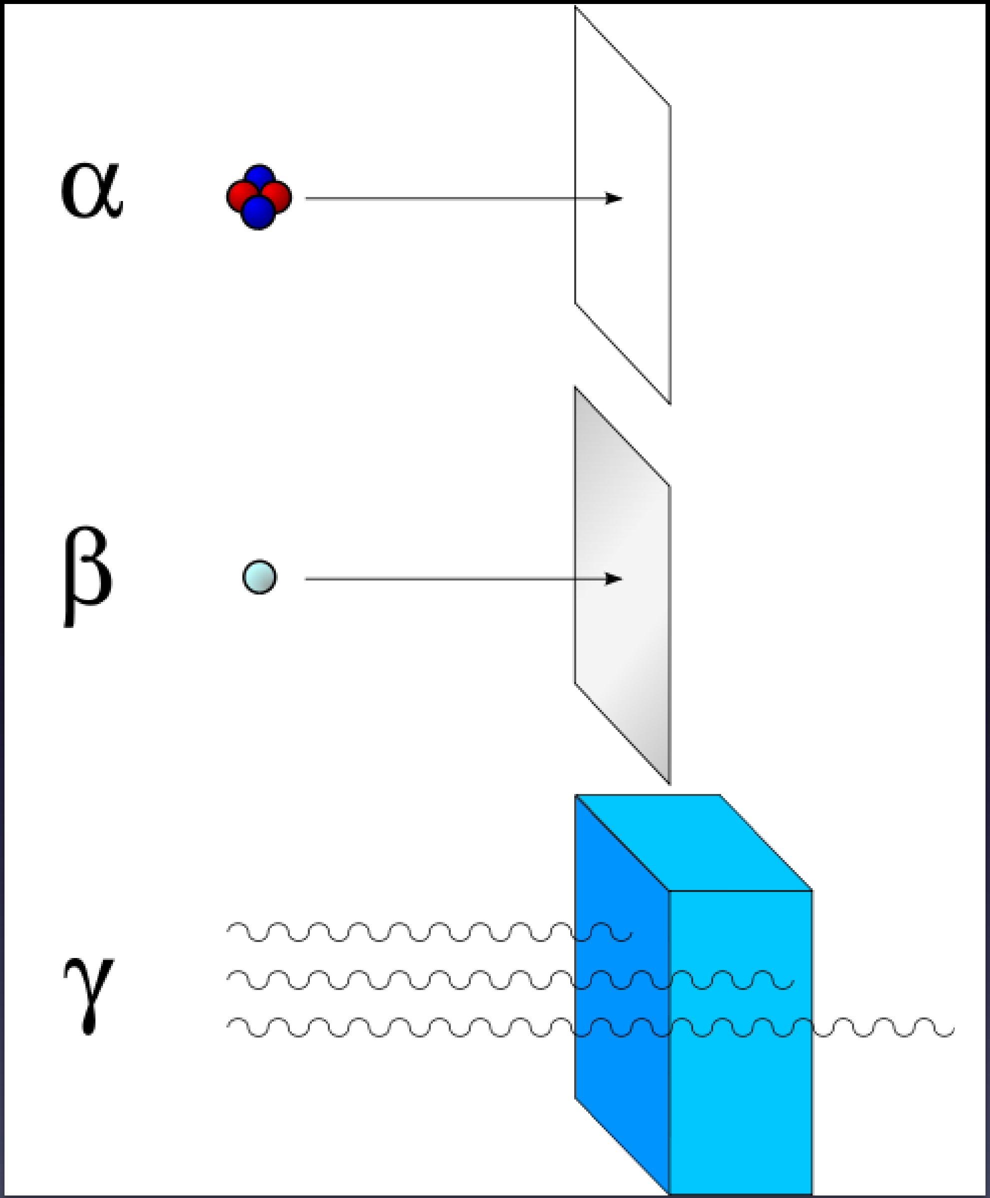
β-Radiation

- β-particles form ions by colliding with the electrons of an atom and removing them from the atom
- β-particles are less ionising than a-particles, but they are lighter, faster and more penetrating
- Most β-particles can be stopped by a thin layer of metal foil, e.g. 18 mm of Aluminium

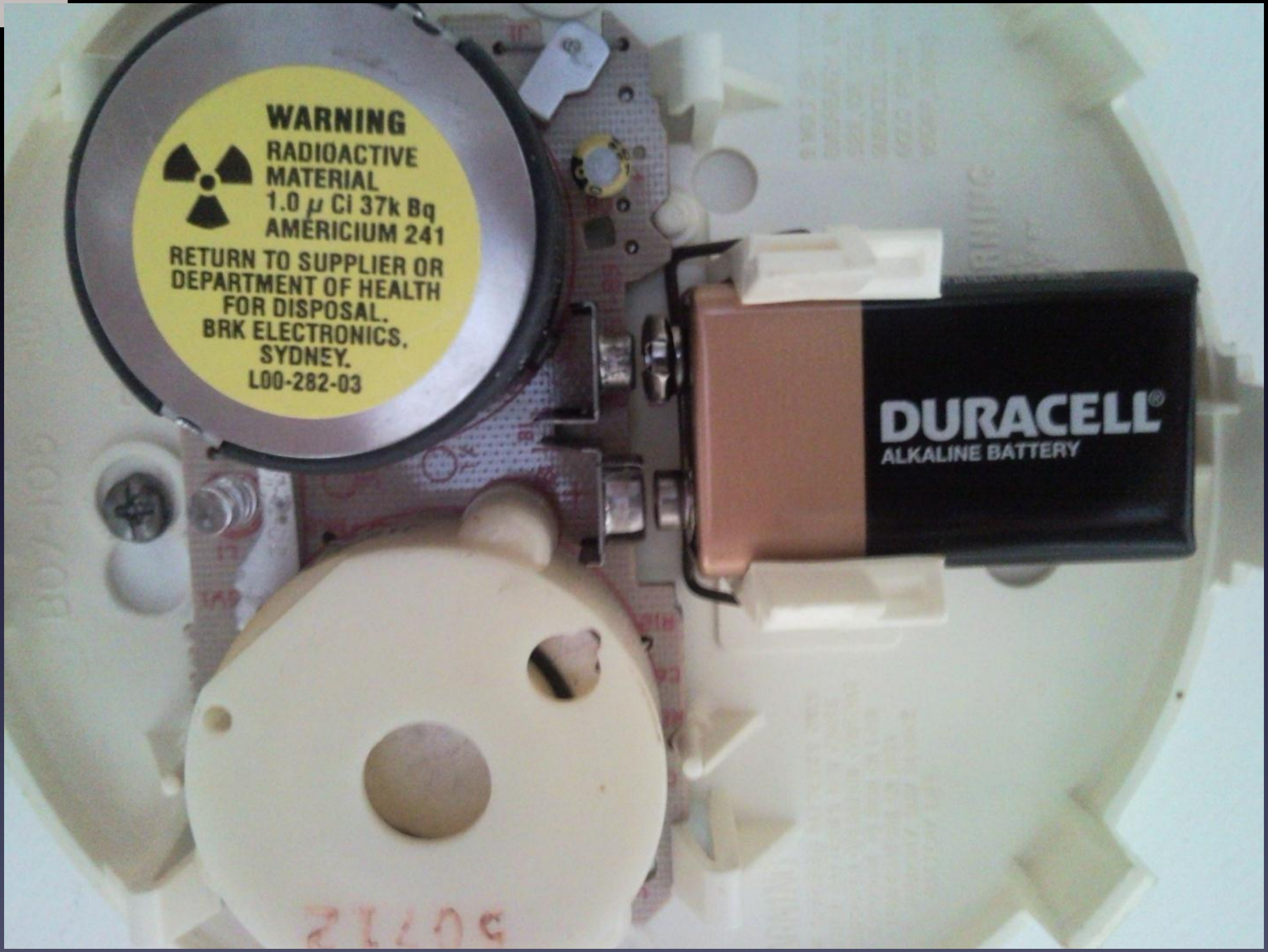
Properties of Radiation

γ-Radiation

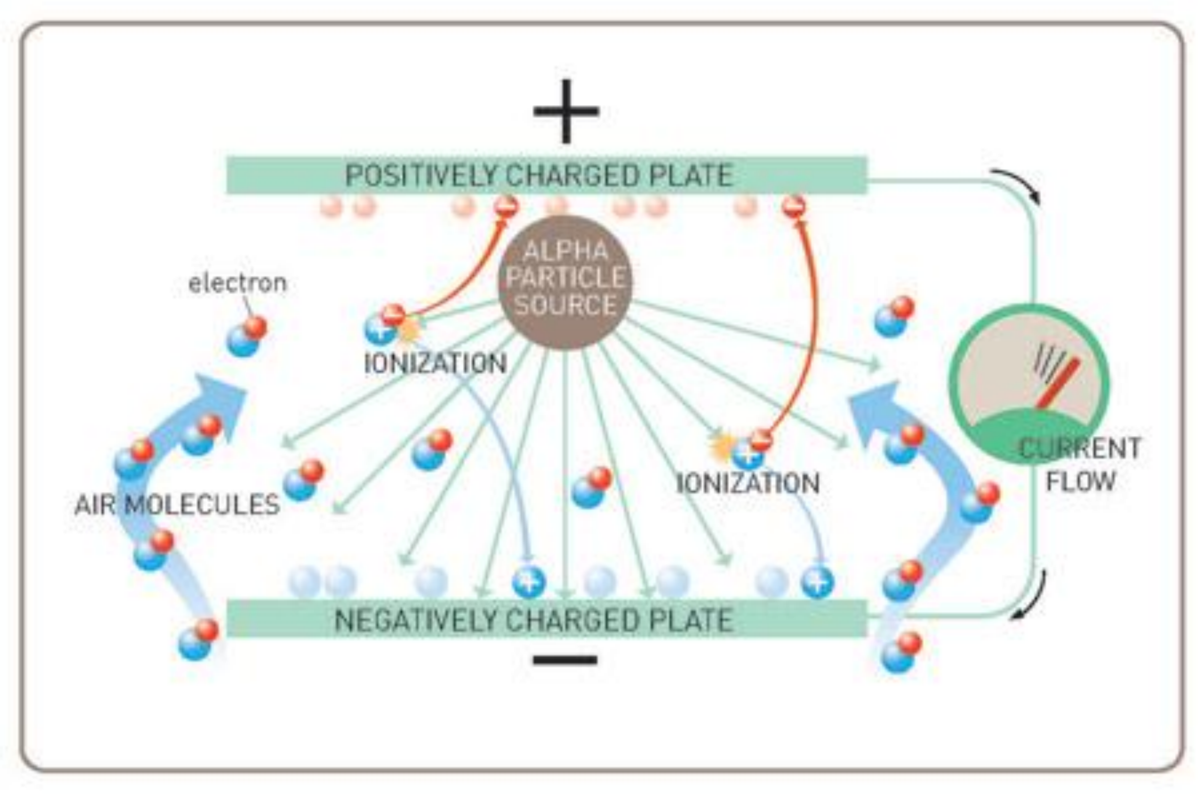
- γ-radiation is the least ionising but most penetrating type of radiation
- γ-radiation travels at the speed of light and has a very high energy
- Most γ-rays can be stopped by a thick block of lead or concrete


α
β
γ

Smoke Detector

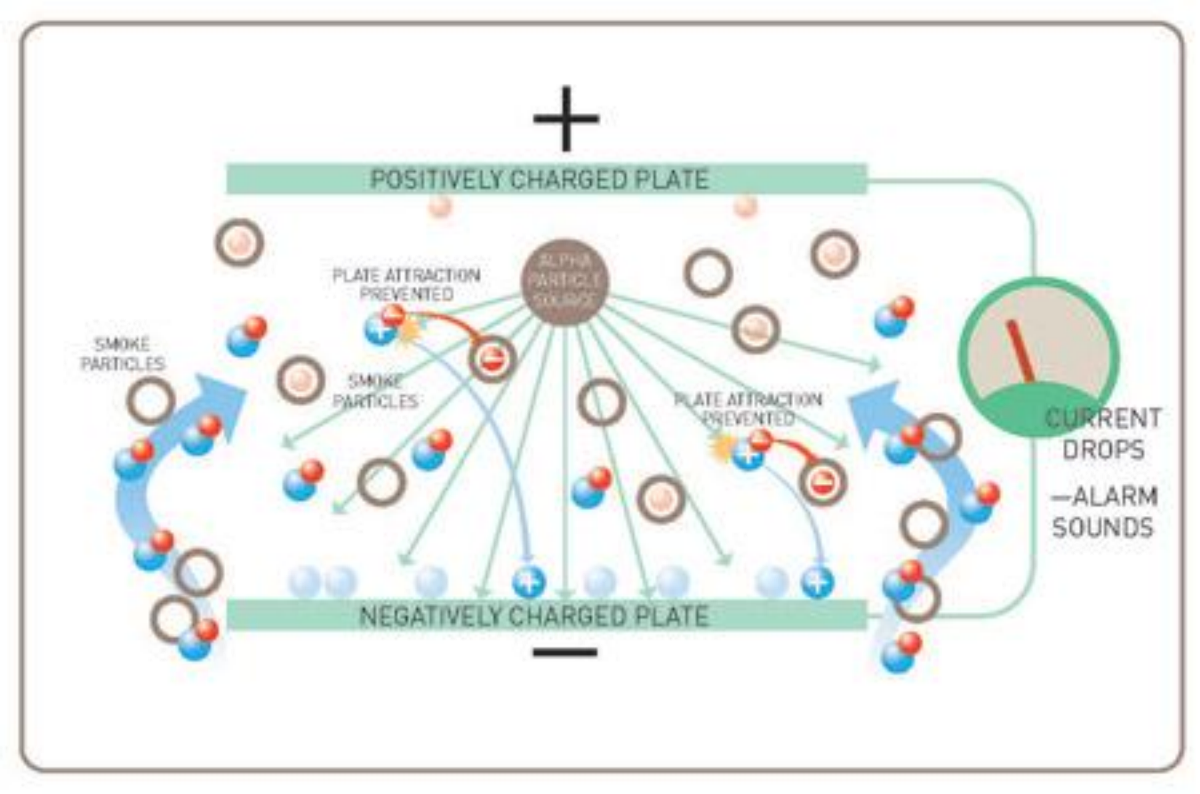


Normal Functioning



α-particles create ions, which move towards the oppositely charged plate, creating a current

With Smoke Present



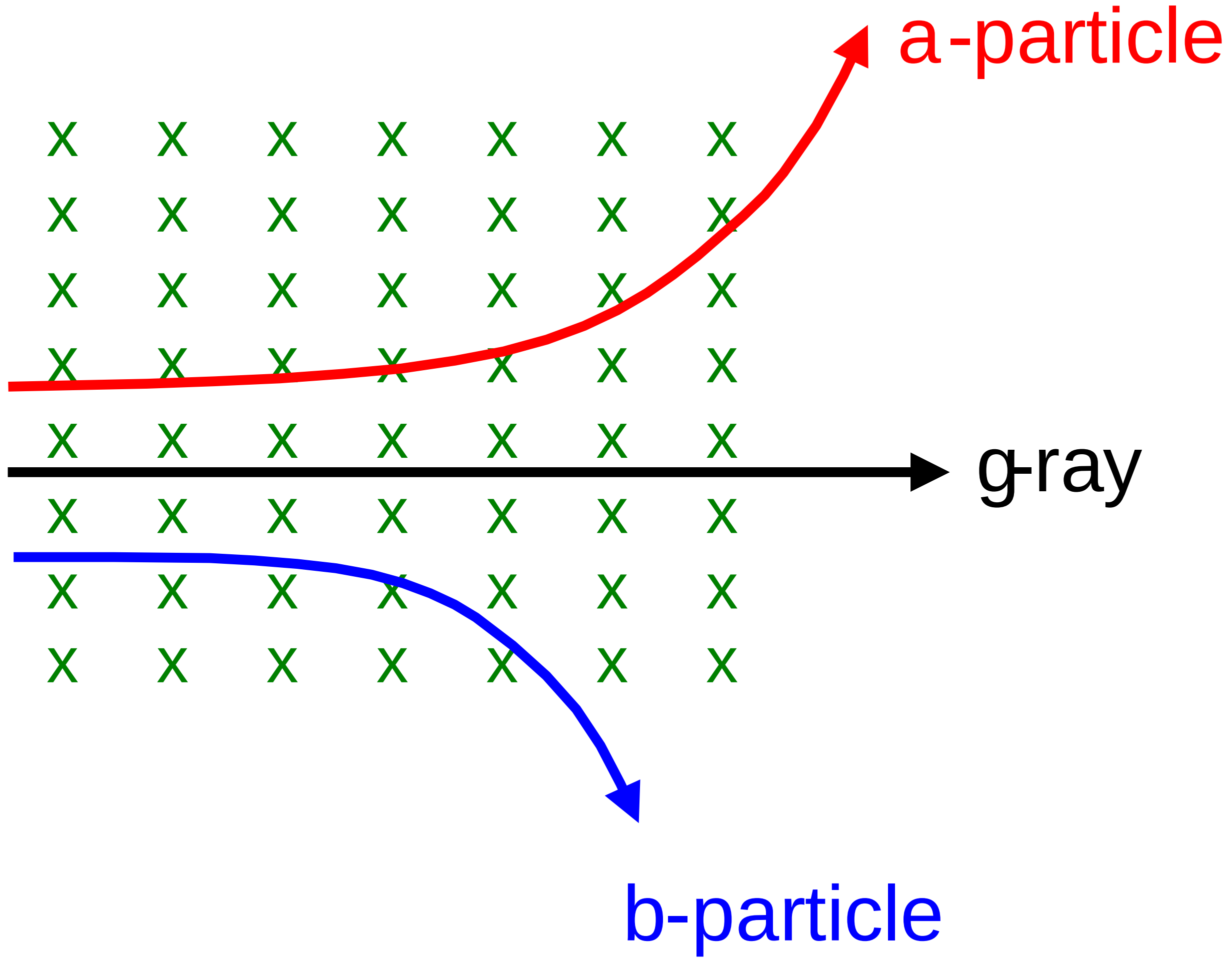
Smoke particles interact with ions, resulting in a reduced current between the plates

Radiation Summary

Type of Radiation	Nature of Radiation	Represented by	Ionising ability	Penetrating ability	Stopped by
α-particle	Helium nucleus	$^4{}_2$He	High	Low	Cardboard
β-particle	Electron emitted from a nucleus	$^0{}_{-1}\beta$	Not as high as α-particles	Higher than α-particles	Sheet of metal
γ-ray	Electromagnetic radiation		Least ionising	Very high	Block of lead

Radioactivity in a Magnetic Field

- The 3 types of radiation behave differently in a magnetic field
- α-particles carry a positive charge, β-particles carry a negative charge, so they are deflected in opposite directions when travelling through a magnetic field (right-hand-slap rule)
- γ-rays are not charged and so are un-deflected in a magnetic field


a-particle
g-ray
b-particle

Radioactive Half-Life

- Every radioactive substance has a specific **half life** (τ or $t_{1/2}$)
- The half life is the amount of time it takes for half of a sample of a radioactive substance to decay (or the radioactivity to decrease by half)
- Radioactive decay is independent of the temperature or chemical context of the atom
- The timing of when any given radioactive atom will decay is random and is a matter of statistical probability

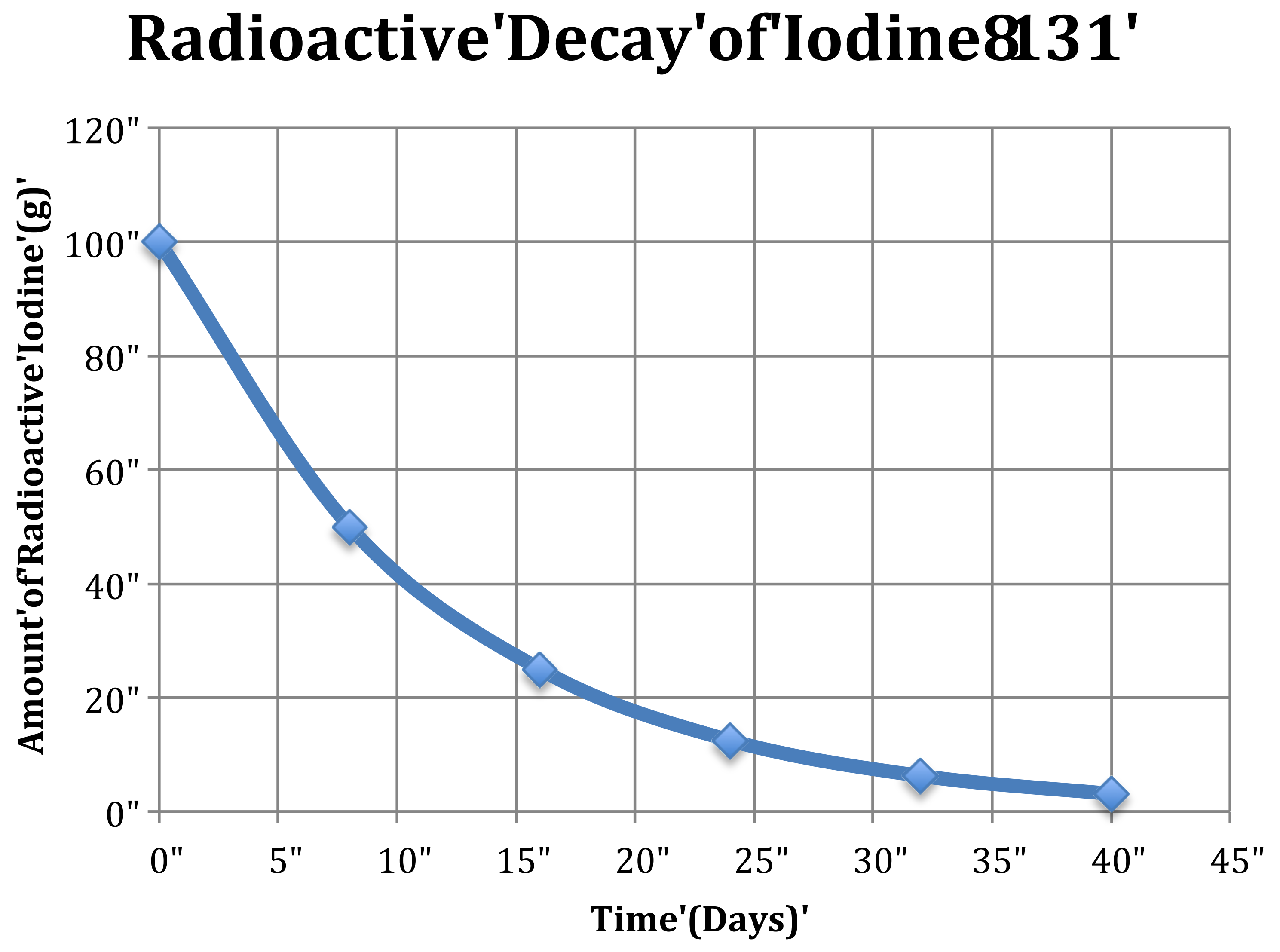
Radioactive Half-Life

- Consider a 100 g sample of iodine-131, which has a half life of 8 days
- After 8 days (1 half life), approximately 50 g of the sample will have decayed, and 50 g will still be radioactive
- After another 8 days (2 half lives), approximately 75 g of the sample will have decayed, and 25 g will still be radioactive
- After another 8 days (3 half lives), approximately 87.5 g of the sample will have decayed, and 12.5 g will still be radioactive

Radioactive-Decay Curves

- A graph of radioactivity vs time is called a **radioactivity-decay curve**
- Radioactivity-decay curves show an exponential decrease in the number of radioactive particles remaining

Radioactive-Decay Curves



Nuclear Fission and Fusion

Nuclear Reactions

- The following rules apply in nuclear reactions:

1. Charge is conserved
2. The total number of nucleons is conserved
3. Mass-energy is conserved
4. Linear momentum is conserved

Nuclear Fission

- **Nuclear fission** is when a heavier nucleus splits into two smaller nuclei and releases energy and, usually, some particles

For example,

$$^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3\,{}^{1}_{0}n$$

$$[{}^{1}_{0}n \rightarrow {}^{1}_{1}p + {}^{0}_{-1}\beta]$$

Critical Mass

- The **critical mass** of a fissionable element is the mass required for a chain reaction to occur
- This happens when neutrons released from a fission reaction are captured by other heavy nuclei, making them unstable, and causing another fission reaction with further release of neutrons

Chernobyl Disaster

Nuclear Fusion

- **Nuclear fusion** is when two smaller nuclei join (fuse) to form a larger, more stable nucleus

$${}^{2}_{1}H + {}^{3}_{1}H \rightarrow {}^{4}_{2}He + {}^{1}_{0}n$$

Advantages of Fusion

- The advantage of fusion is that the reactants are readily obtained and it does not produce radioactive products
- The problem with fusion is that very high temperatures and pressures are required for the reaction to occur
- Nuclear fusion is the reaction that powers stars
- The fusion reaction in our Sun is predominantly the fusion of Hydrogen into Helium

Mass-Energy Equivalence

- Einstein’s famous equation describes the relationship between energy and mass

$$E = mc^2$$

- Essentially, we can consider matter to be a form of stored energy
- Overall, **mass-energy** is conserved, e.g. in a nuclear reaction some mass may be converted to electromagnetic energy, but the total mass and energy in the reaction is conserved

m = mass, kg

E = energy stored in that mass, J

c = speed of light = 2.9979×10^8 m.s^{-1}

Energy Release in Fission and Fusion

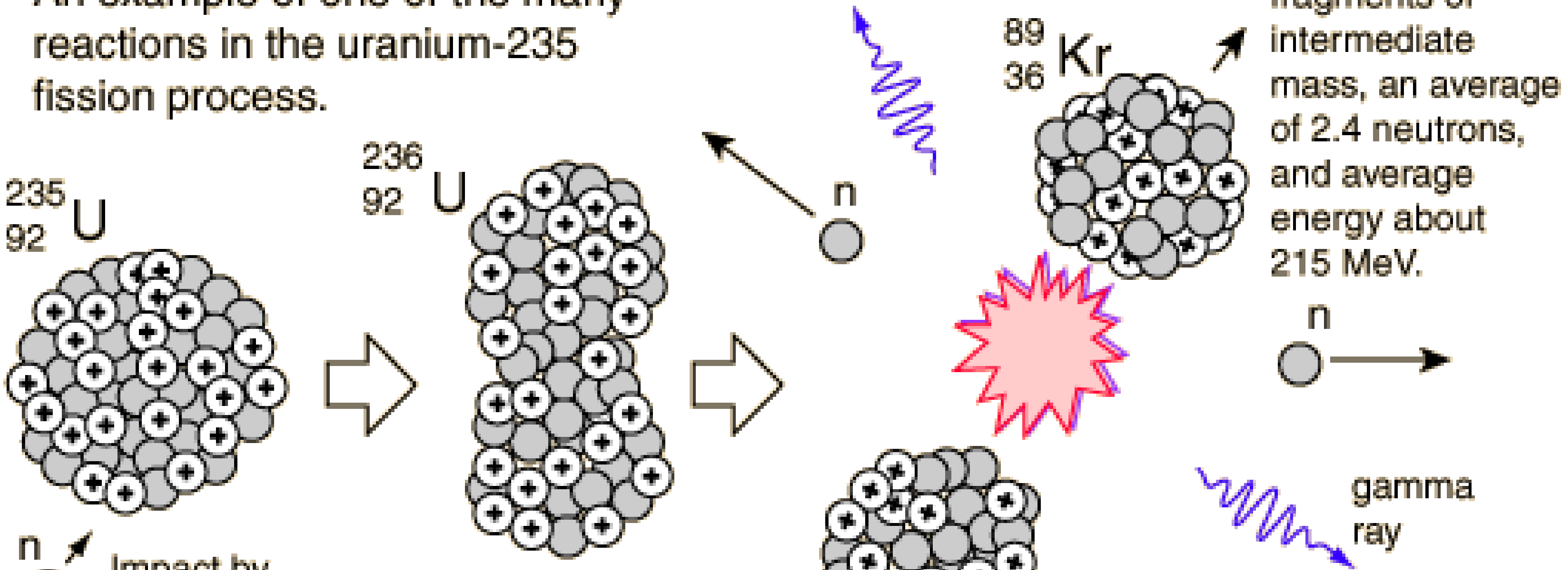
- To calculate the energy released in a nuclear reaction:
  - Add up the total mass on the left-hand side of the reaction and add up the total mass on the right-hand side of the reaction
  - Determine the mass deficit by subtraction
  - Calculate the energy released using $E = mc^2$
- Note: if the mass of the products is greater (i.e. there has been a mass increase) the reaction is not energetically favourable and will not proceed without the *input* of energy

Energy Release in Fission and Fusion

- The energy released in a nuclear reaction is in the form of kinetic energy of the particles released and gamma rays
- The energy released by the oxidation of one carbon atom (e.g. in a coal-fuelled power plant) is about 4 eV
- The energy released by the fission of one uranium atom is about 150 MeV
- The energy released by the fusion of a hydrogen-2 nucleus and a hydrogen-3 nucleus is about 18 MeV

Nuclear Power

An example of one of the many reactions in the uranium-235 fission process.

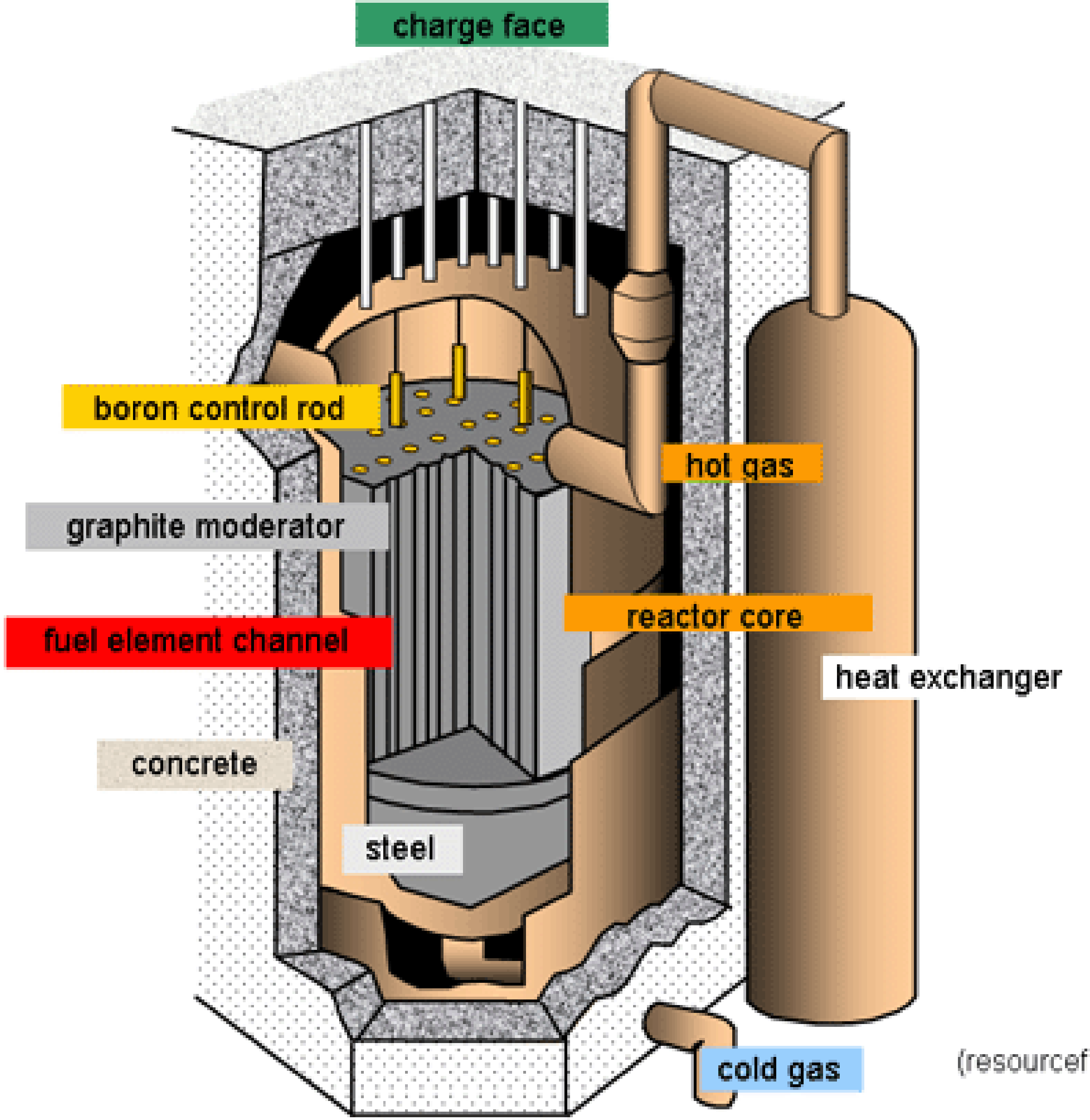


Impact by slow neutron with energy on order of an eV.

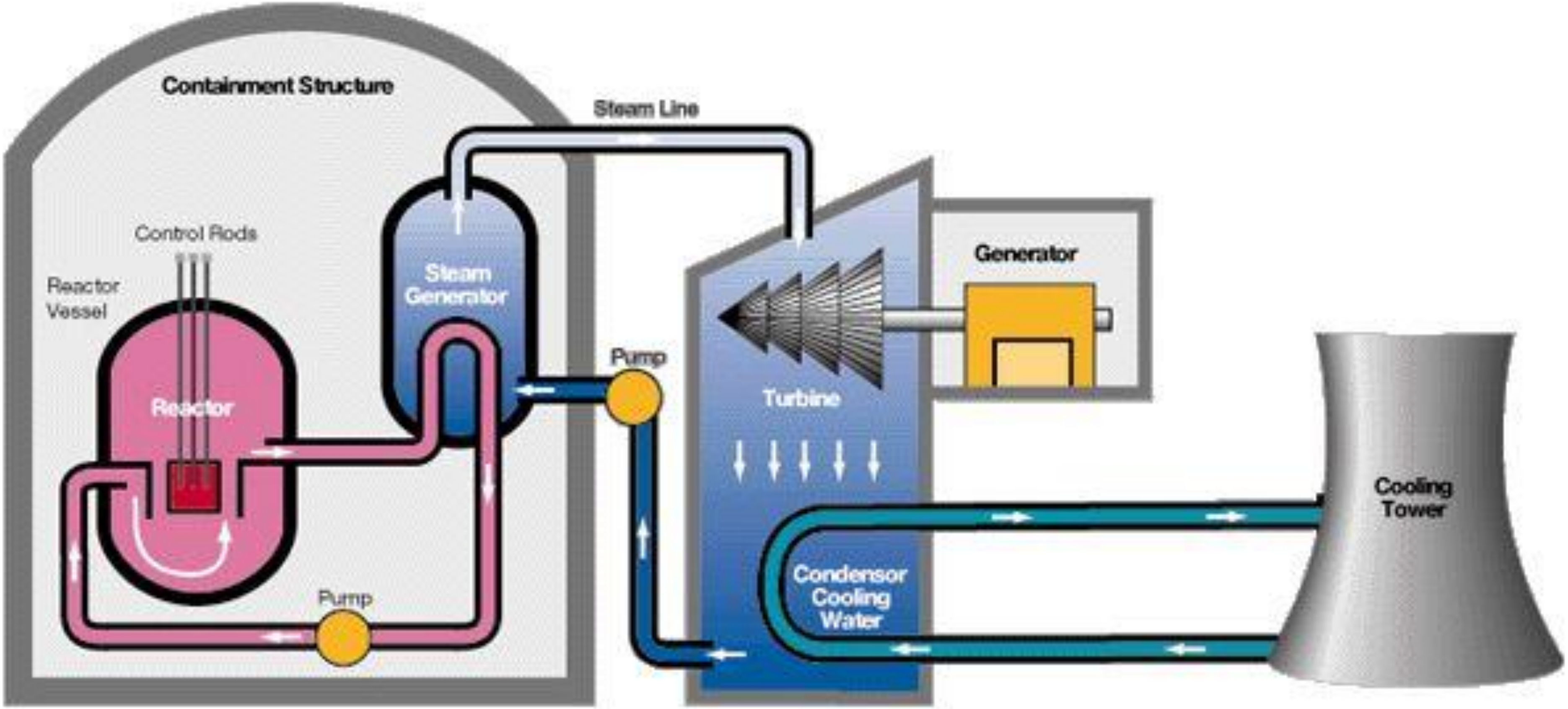
U-236 compound nucleus is unstable, oscillates.

Fission yields fragments of intermediate mass, an average of 2.4 neutrons, and average energy about 215 MeV.

Neutrons can initiate a chain reaction.



(resourcefulphysics.org)


Containment Structure
Steam Line
Control Rods
Reactor Vessel
Steam Generator
Generator
Reactor
Pump
Turbine
Cooling Tower
Condensor Cooling Water
Pump

Calculating Nuclear Power

- When calculating the power requirement/production of a nuclear power station consider:
  - Power = Work/time
  - The efficiency of the power station
  - The energy released per atom

Nuclear Power – Exercise 1

- A nuclear power station produces 24 MW of power
- The efficiency of the reactor is 32%
- In the fission of one uranium-235 nucleus 3.2×10^{-11} J of energy is released

→ Determine the mass of uranium required to run the power station for one year

Nuclear Power – Exercise 2

- The Sun produces 3.8736 x 10^{26} W of power
- The efficiency of the Sun is 100%
- The mass of the sun is 1.9891 x 10^{30} kg

$${}^{2}_{1}H + {}^{3}_{1}H \rightarrow {}^{4}_{2}He + {}^{1}_{0}n$$

→ If we assume all of the mass is Hydrogen, how long will the Sun burn for?