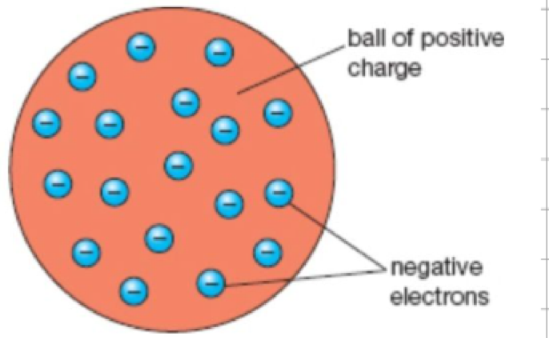
Probing Matter

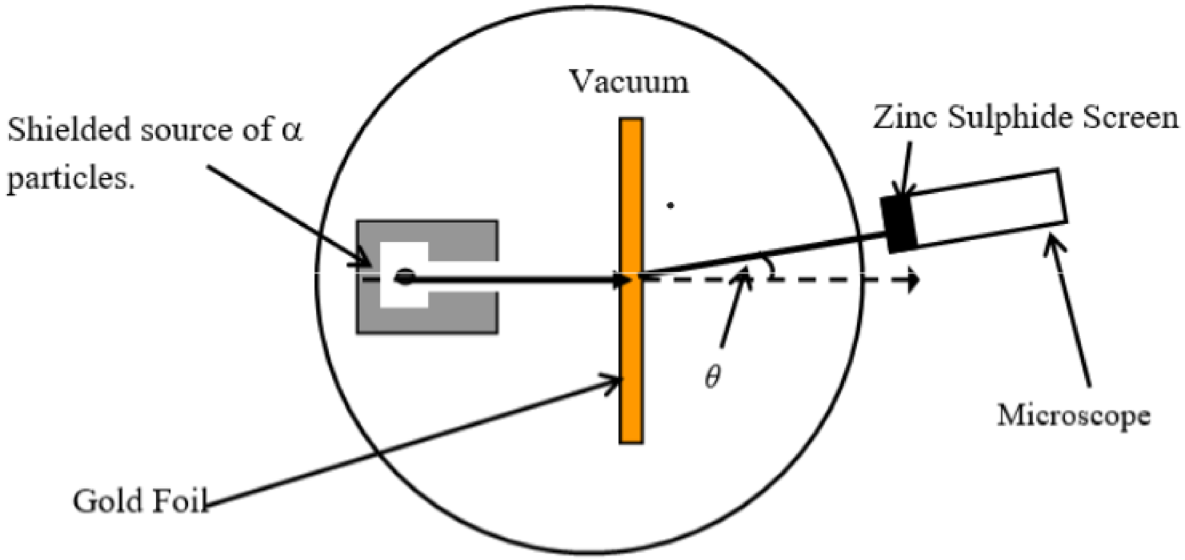
Dalton - proposed the concept of Atomic theory
Thomson - discovered the electron (more later)



- proposed the plum pudding model

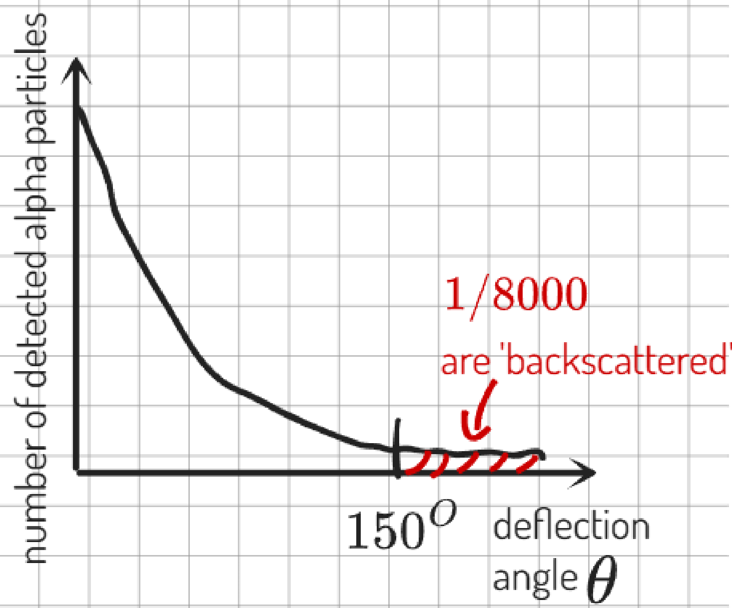
Rutherford's Alpha Scattering Experiment

Rutherford hypothesised that all alpha particles should have passed through the gold leaf with little to no deflection.



The team found that:

- Most of the alpha particles passed straight through as expected.
- Some were deflected through a measurable angle.
- Very few (1 in 8000) were 'backscattered'

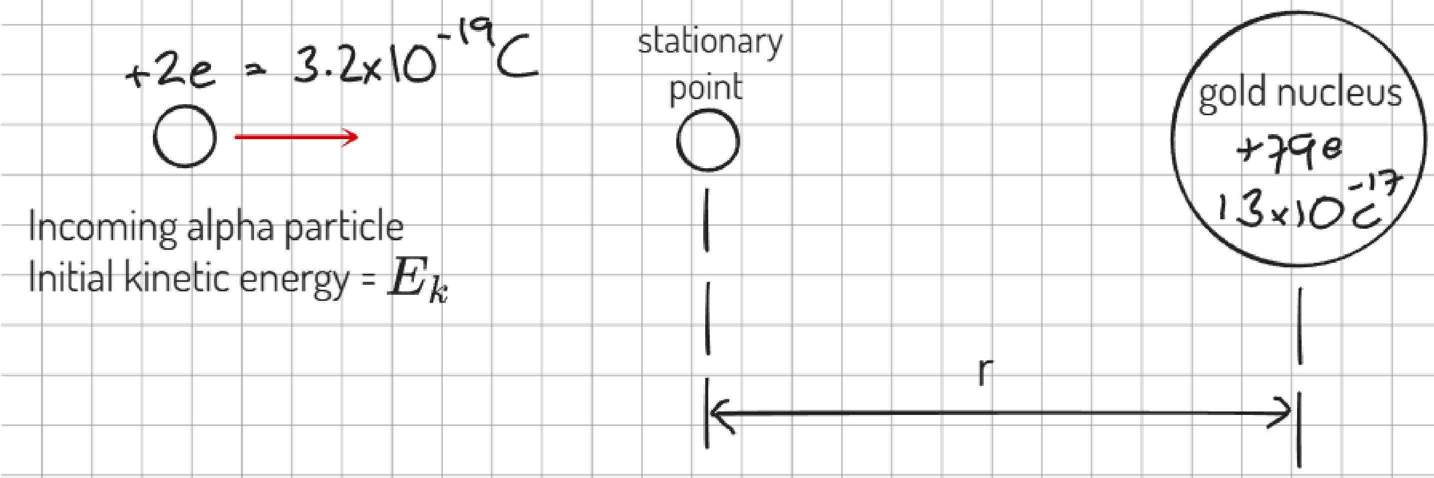


Rutherford concluded that:

- The atom is mostly empty space, but contains a small region which is electrostatically charged.
- This region is positive and more massive than an alpha particle.

Rutherford estimated the radius of the nucleus to be around 1 fm.

Closest approach



The alpha particles have an approximate energy of 5 MeV. As they approach the nucleus (assuming a perpendicular rebound) there will be a stationary point where all of the kinetic energy will have been transferred to ELECTRICAL POTENTIAL ENERGY store.

$$E_k = E_{ep} \qquad E_{ep} = \frac{qQ}{4\pi\varepsilon_o r}$$

$r \approx 45\ fm$

$$\varepsilon_o = 8.85 \times 10^{-12}\ Fm^{-1}$$

- The contributions from the strong nuclear force are neglected.
- The alpha particle is NOT a point particle on this scale, neither is the nucleus.

Electron Diffraction

Recap: De Broglie

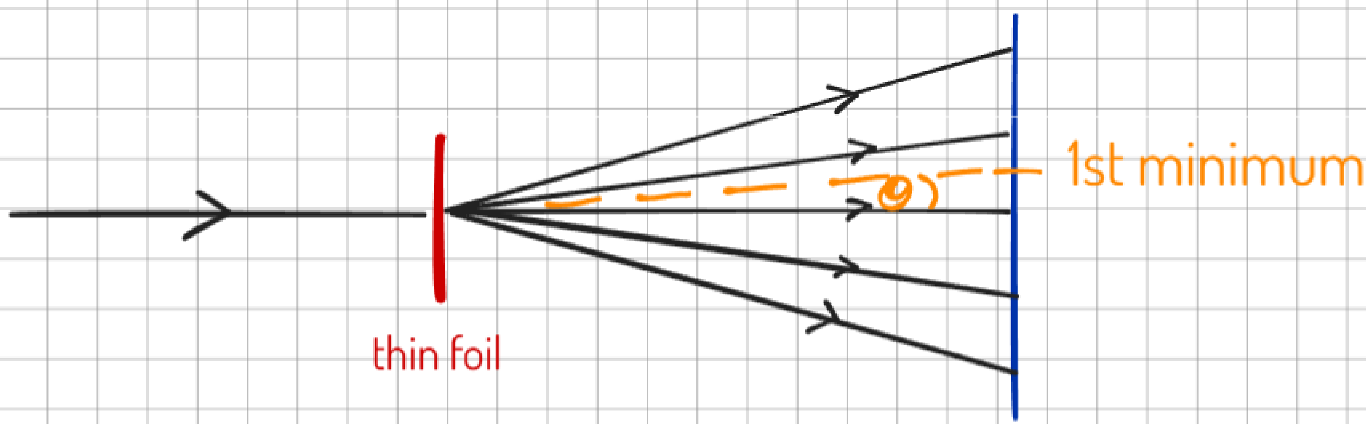
The length at which wave-like properties are probable for a particle.

$$\lambda_{DB} = \frac{h}{p} \qquad \lambda_{DB} = \frac{h}{mc} \qquad \lambda_{DB} = \frac{h}{mc}\left(\frac{c}{c}\right)$$

$$\boxed{\lambda_{DB} = \frac{hc}{E}}$$

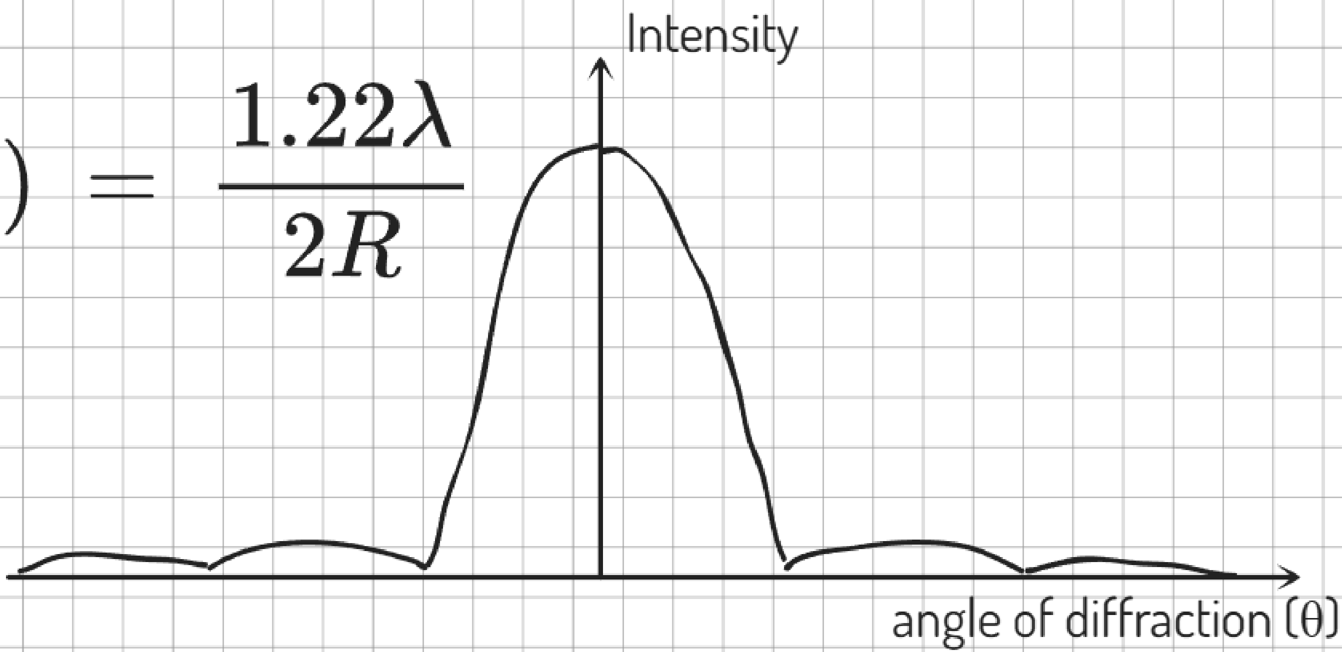
We know that the nuclear radius will be in the order of 10^{-15} m.
So we want the de Broglie wavelength of an incident particle to be similar for diffraction.

This is NOT electron diffraction as we studied it in Y12.
In that instance the atomic lattice was forming a diffraction grating.
In this case, the NUCLEUS is acting as an aperture.

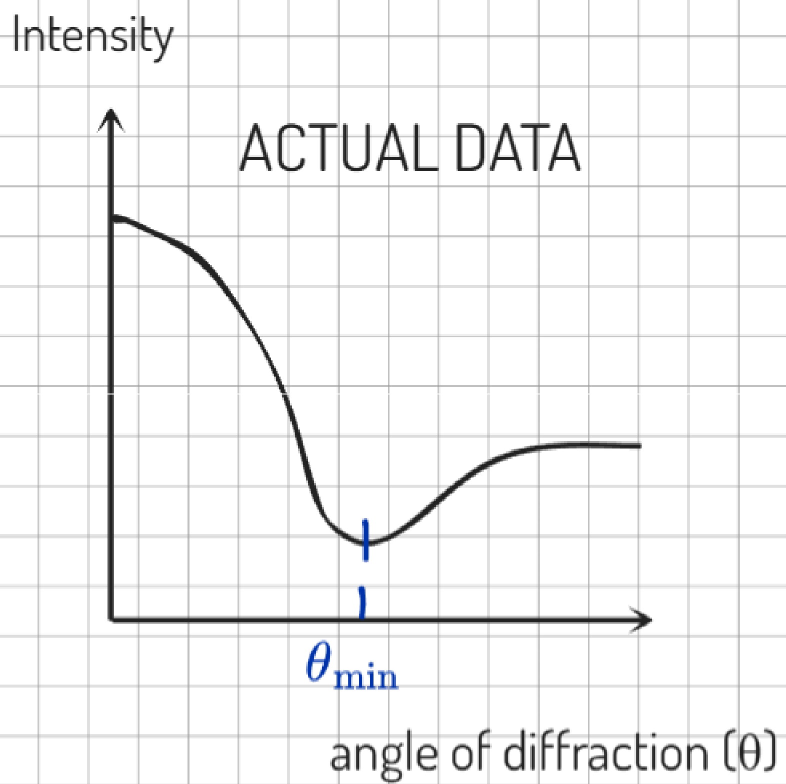


From diffraction theory:

$$\sin(\theta) = \frac{1.22\lambda}{2R}$$



Knowing the angle of the first minimum from the data allows us to calculate the radius of the nuclei by which the electrons were diffracted.



A beam of 300 MeV electrons produce a diffraction pattern from a thin metal target. The first minimum falls at precisely 30^o, estimate the nuclear radius.

$$\lambda = \frac{hc}{E} = \frac{6.63\times10^{-34} \times 3\times10^{8}}{(300 \times 1.6\times10^{-13})} \quad \checkmark_1$$

$$\lambda = 4.1\times10^{-15}\,m \quad \checkmark_2$$

$$R = \frac{1.22\,\lambda}{2\sin(\theta)} = \frac{1.22 \times 4.1\times10^{-15}}{2\sin(30)} \quad \checkmark_3$$

$$\boxed{R = 5.1\,fm} \quad \checkmark_4 \quad (5.1\times10^{-15}\,m)$$

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

pd across electron gun (accelerating pd)

$$mv^2 = 2eV$$

$$m^2v^2 = 2meV$$

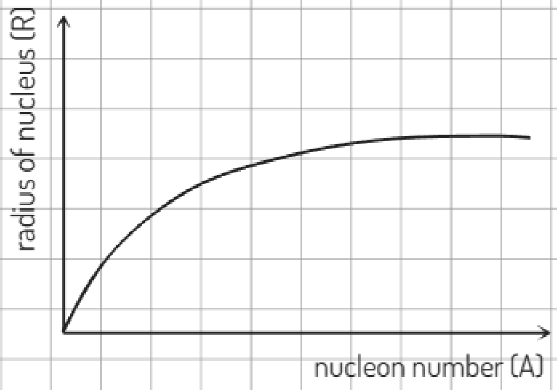
$$mv = (2meV)^{1/2}$$

$$\lambda = \frac{h}{mv} = \frac{h}{(2meV)^{1/2}}$$

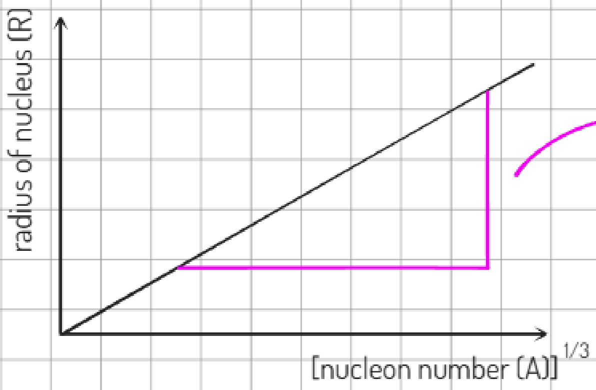
$$\sin\theta = \frac{1.22\,\lambda}{2R} = \frac{1.22\,h}{2\sqrt{2}\,R\,(meV)^{1/2}}$$

FOR INFO

Nuclear Radius and Density



$^{A}_{Z}X$



$gradient = R_0 = 1.4\ fm$

$$R = R_0 A^{1/3}$$

radius of any nucleus

$R^3 \propto V$ and $R^3 \propto A$

$$V = \frac{4}{3}\pi R^3$$

mass of nucleus = $A\, m_{nucleon}$

(assuming p and n have similar mass)

$$\rho = \frac{A\, M_{nucleon}}{\frac{4}{3}\pi (R_0 A^{1/3})^3}$$

$$\boxed{\rho = \frac{3 M_{nucleon}}{4 \pi R_0^3}}$$

EVERY TERM IS CONSTANT

ALL nuclei have a density of $1.45 \times 10^{17}\ kgm^{-3}$

The density of an atom is in the region of $10^3 - 10^5$

This suggests that:

- Most of the atoms mass is in the nucleus.
- The nucleus is VERY small compared to the atom.
- The atom is mostly empty space (to account for the significant decrease)
- We already know that they atom is charged.

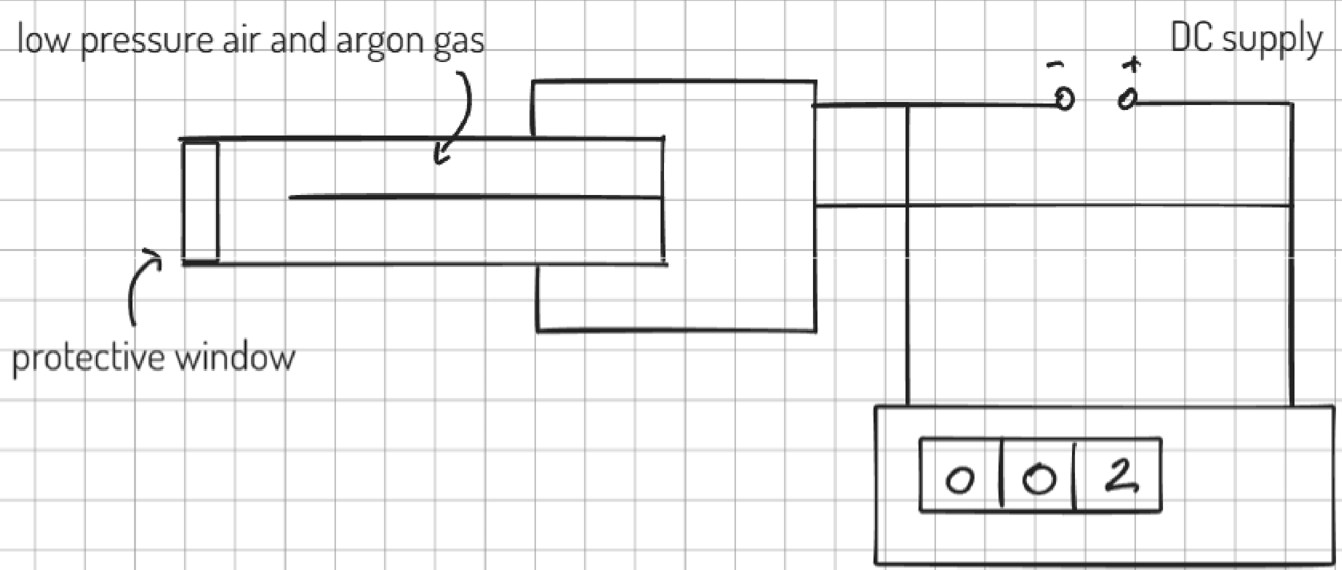
Detecting Ionising Radiation

Activity

The ACTIVITY of a radioisotope is the number of DECAYS that occur, on average, per second.
(Nuclear decay is a RANDOM process)

Alpha, Beta and Gamma are forms of IONISING RADIATION. They cause atoms to lose an electron and create ion pairs, in the material as they pass through.
Production of the ions transfers kinetic energy from the radioactive particle, so eventually it will come to rest.

Ion pairs can be detected by a Geiger-Muller tube.



How a GM tube works

- A thin central wire which runs parallel to an earthed metal cylinder. The wire produces a strong electric field within the cylinder.
- Any electron produced by ionisation will accelerated towards the wire. (and the resulting ion is accelerated away from the wire towards the cylinder). On the way collides with the neutral atoms within the cylinder, liberating other electrons, causing an AVALANCHE of electrons and ions. (Typically 10^8 per original event)

The gas needs to be under low pressure to allow electrons to accelerate between collisions.

- The arrival of this avalanche at the central wire triggering a PULSE of current, which triggers a COUNT.

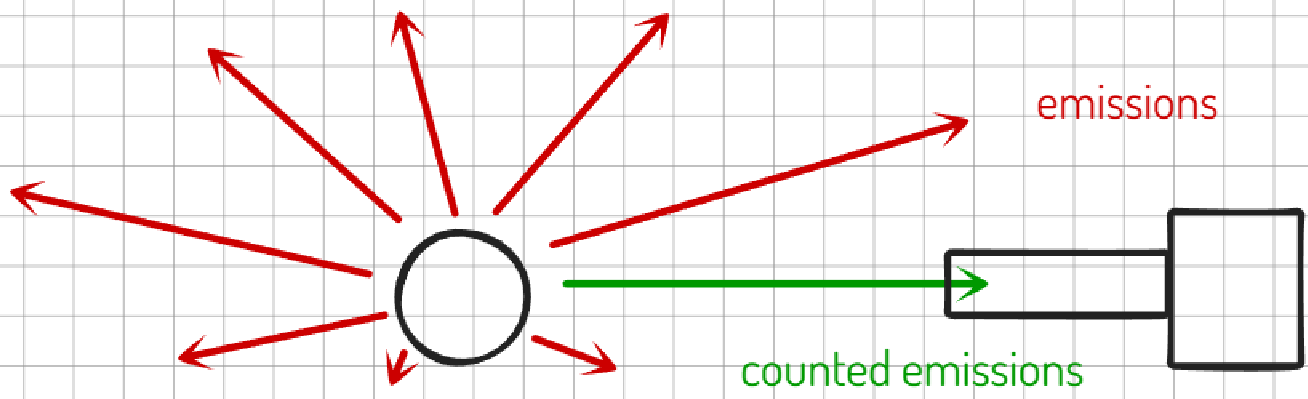
- A higher potential wire will give a more sensitive GM tube.

- There is region of insensitivity after each ionisation called DEAD TIME. The maximum is 300 cps.

Count Rate

The number of counts per second

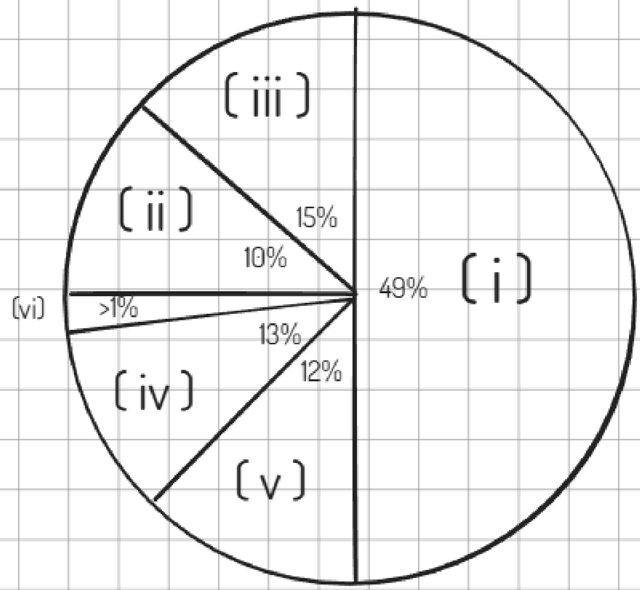
Why are count rate and activity NEVER the same?



Mode of Decay	Symbol(s)	Ionising power	Range (and why)	Limits on Penetration
ALPHA	${}^{4}_{2}\alpha$ / ${}^{4}_{2}He$	HIGH 10,000 ion pairs per mm of air	LOW 3-5 cm in air before they lose all Kinetic Energy and come to rest.	Typically absorbed by a single sheet of paper.
BETA	${}^{0}_{-1}\beta$ / ${}^{0}_{-1}e^{-}$	MODERATE 100 ion pairs per mm of air	MODERATE 50-100 cm in air before they lose all Kinetic Energy and come to rest.	Typically absorbed by a few millimetres of aluminium metal.
GAMMA	${}^{0}_{0}\gamma$	LOW 1 ion pair per photon	HIGH 1km+ range in air before they all photons are absorbed.	Typically absorbed by many centimetres of lead or several metres of concrete.

Working with Radioisotopes

Background Radiation



i) Air - contains radioactive Radon gas
ii) Food and Drink - several foods and drinks contain dissolved radioisotopes
iii) Artificial sources - several rocks contain Th-232 and U-238. Dose varies by region
iv) Medical sources - X-rays, Gamma rays etc
v) Cosmic rays - High energy photons from Sun
vi) Other - nuclear power, fallout, weapons testing, industrial techniques

Background radiation presents a source of SYSTEMATIC ERROR in experimentation. When we record the COUNT RATE the reading will be slightly elevated. We can produce a CORRECTED COUNT RATE by subtracting the MEAN BACKGROUND COUNT from all data sets. (Generally the background count is obtained before, during and after the experiment and a mean is taken)

Dose

CONTAMINATION - Occurs if an object has a radioactive material introduced into or onto the surface of it. The object is (temporarily) radioactive.
IRRADIATION - Exposing objects to ionising radiation. This can damage cells in living things. The object is NOT radioactive.

Dose is measured in Grays

$$D = \frac{E}{m}$$

1 Gray = 1 Joule per kilogram

However this value is generic and does not consider risk factors.

Effective Dose [H] is measured in Sieverts (or more commonly milliSieverts)

$$H = W_R D$$

TYPE	W_R
Xray, Gamma, Beta Minus	1
Protons	2
Alpha, Fission products	20

Using Radioisotopes

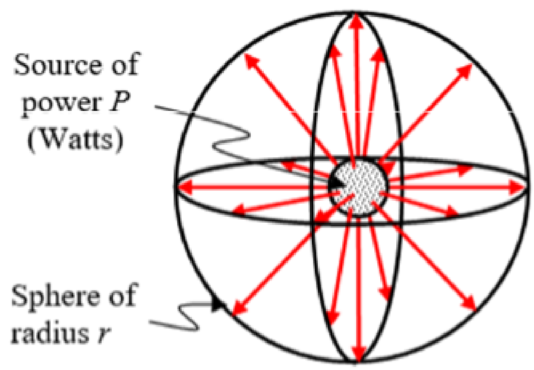
When handling radioisotopes for experimental purposes the researcher should:
- Minimise exposure time - do not use for longer than needed.
- Maximise distance to the source - use tongs and keep at arms length.
- Store in a lead lined box when not in use.

The Inverse Square Law

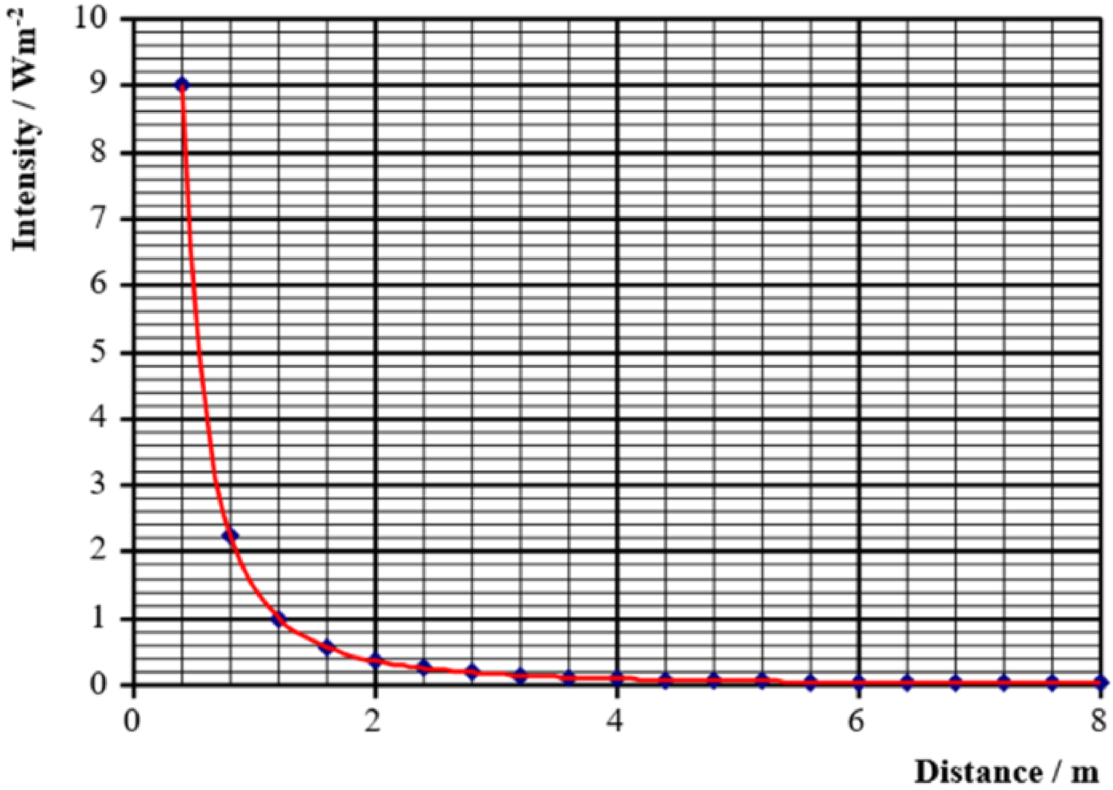
Intensity

The intensity of a wave passing perpendicularly through a surface is defined as the ENERGY passing per unit AREA per SECOND through the surface.

It is measured in Watts per square metre.



$$I \propto \frac{1}{r^2}$$



At a reference distance of r_0 , the intensity is I_0
So at any given value of r , the intensity will be:

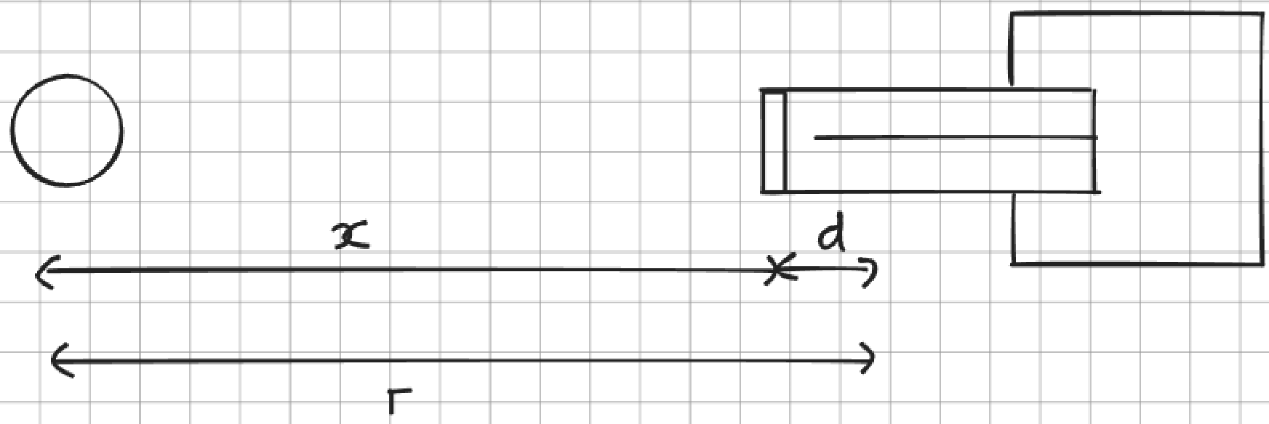
$$I_0 \propto \frac{1}{r_0^2} \qquad I_0 = \frac{k}{r_0^2} \qquad I_0 r_0^2 = k$$

$$I_0 r_0^2 = I r^2$$

$$\boxed{I = \frac{I_0 r_0^2}{r^2}}$$

To study the variation in intensity of gamma radiation we will record the count rate against distance with a Geiger-Muller tube and ruler.

Note: we assume that Gamma radiation is monochromatic given by $E = hf$



where N - the number of incident photons
E - energy of each photon (hf)
A - cross-sectional area of the window
t - exposure time

At r

$$I = \frac{NE}{At} \qquad \frac{N}{t} = \frac{IA}{E}$$

$$\text{Count rate} = \frac{N}{t} \times \text{efficiency}$$

$$\text{Count rate} = \frac{IA}{E} \times \text{efficiency}$$

constant

$$C \propto I \qquad C \propto \frac{1}{r^2} \qquad C \propto \frac{1}{(x+d)^2}$$

$$C = \frac{K}{(x+d)^2}$$

$$(x+d)^2 C = K$$

$$(x+d) C^{1/2} = K^{1/2}$$

$$x + d = \frac{K^{1/2}}{C^{1/2}}$$

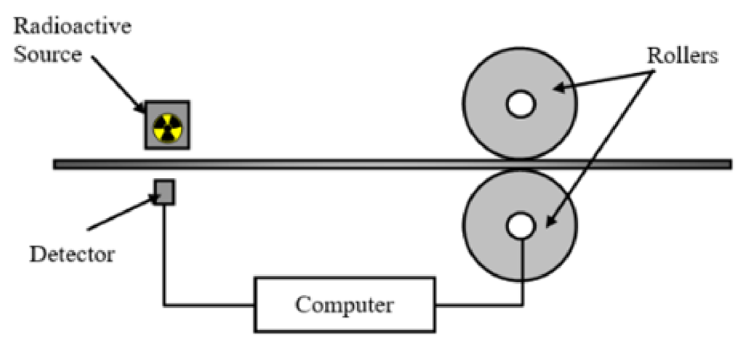
$$x = K^{1/2} \frac{1}{C^{1/2}} - d$$

$$y = m x + c$$

Uses of Radioisotopes

Thickness Control

Gamma radiation can be used to control the thickness of rolled steel in industry.



A gamma source and detector are placed on opposite sides of the rolled material.
The computer monitors the count rate and adjusts the separation of the rollers appropriately.

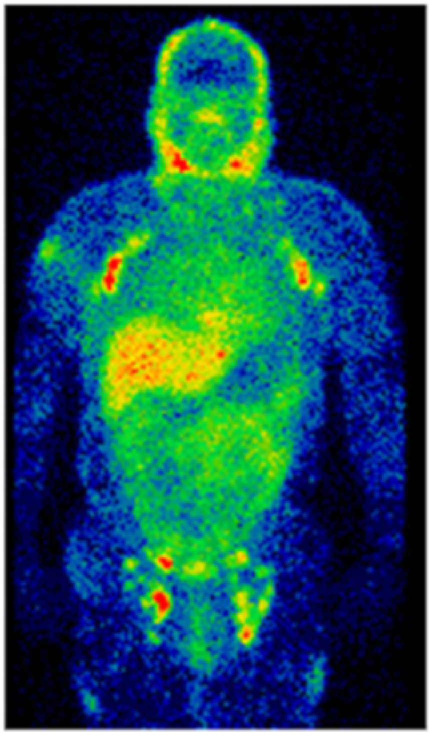
Gamma is most appropriate for steel as:
- Alpha will be fully absorbed by the air between source and the steel.
- Beta minus will be fully absorbed by the steel.

Gamma is not appropriate for paper as the reduction in count rate would not be significant, Beta minus must be used here.

Tracer techniques

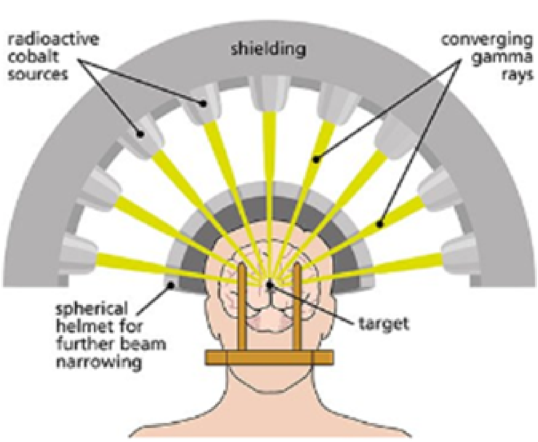
Radioisotopes can be introduced into a system to detect leaks or faults. Radioactive gases can be fed into underground pipes to find leakages.

Technecium-99 can be used as a medical tracer. It emits gamma radiation which can be easily detected outside the body. It has a half-life of 6 hours so has a RELATIVELY CONSTANT ACTIVITY for the duration of the procedure.



Short scans pose little risk to the patients.
THE BENEFITS MUST OUTWEIGH THE RISK

Radiotherapy



Internal radiotherapy involves a source being introduced into the tumour itself. (Usually a needle filled with an alpha source)

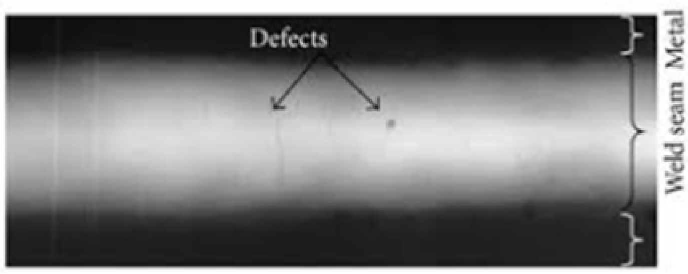
External therapy uses a 'gamma knife'. Multiple beams minimise exposure to healthy cells.

Radiophotography

It is difficult to assess the quality of a joint between two pieces of metal. A gamma sources is placed in the joint between the welded pieces.

The joint is then wrapped in photographic film.

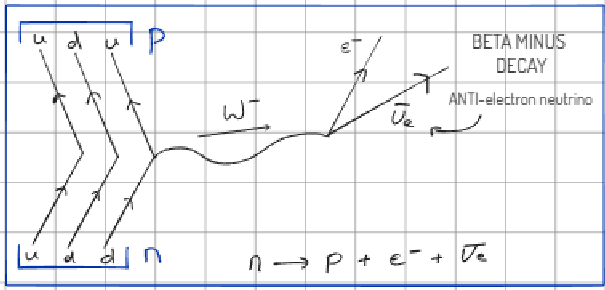
In poor joints the discolouration is non-uniform.

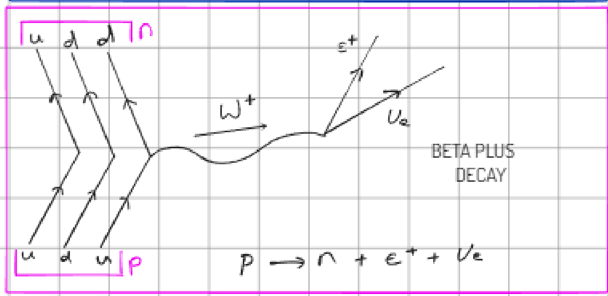


Sterilisation

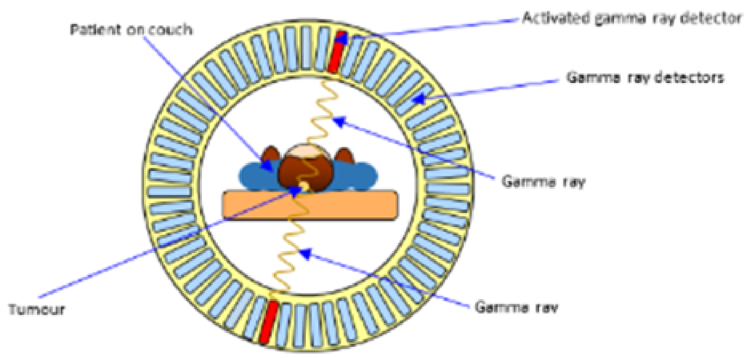
Tinned food is exposed to ionising radiation to ensure that there are no live micro-organisms present in the tin.

PET Scanning





In beta plus decay a proton decays into a neutron and positron (and an electron neutrino).
The positron almost immediately undergoes an annihilation event producing a PAIR OF PHOTONS, moving in OPPOSITE DIRECTIONS (to conserve momentum).



Positron emission tomography (PET) scanner

Multiple annihilations allow us to pinpoint the location of the tumour.

Radio-carbon Dating

Carbon-14 is formed in our atmosphere by N-14 absorbing neutrons.
It is then incorporated into living things.

The rate of production in the atmosphere is approximately equal to the rate of decay within the organism.

The amount of C-14 in a living organism is roughly CONSTANT.

When that organism dies,
decay continues but uptake ceases.

C-14 has a half-life of 5370 years, so we can date artefacts from 500 - 500,000 years old.

Modes of Decay

Alpha

A Helium nucleus, composed of 2 protons and 2 neutrons.

Mass - 4u　　　　Charge - +2e

$u = 1.67 \times 10^{-27}$ kg　　　　$e = 1.6 \times 10^{-19}\ C$

An alpha particle is HIGHLY IONISING, the strong positive charge pulls electrons from nearby atoms (often from the valence orbital)

A passing alpha particle produces around 10,000 ion pairs per millimetre of air.

Alpha particles will be slightly deflected by a strong electric or magnetic field.

Typically alpha particles are released by 'heavy' nuclei and have energies of a few MeV.

$${}^{226}_{88}Ra \longrightarrow {}^{222}_{86}Rn + {}^{4}_{2}\alpha$$

$${}^{235}_{92}U \longrightarrow {}^{231}_{90}Th + {}^{4}_{2}He$$

Beta minus decay

When an unstable neutron decays to a proton via the weak interaction a high speed (approx 98% of c) electron and an electron anti-neutrino are emitted.

Beta particles are moderately liberating around 100 ion pairs per millimetre of air.

This mode occurs in NEUTRON RICH nuclei.

$$^{24}_{11}Na \longrightarrow {}^{24}_{12}Mg + {}^{0}_{-1}e^{-} + {}^{0}_{0}\bar{\nu}_e$$

$$^{14}_{6}C \longrightarrow {}^{14}_{7}N + {}^{0}_{-1}\beta + {}^{0}_{0}\bar{\nu}_e$$

Beta plus decay

Both modes of beta decay are strongly deflected by an electromagnetic field

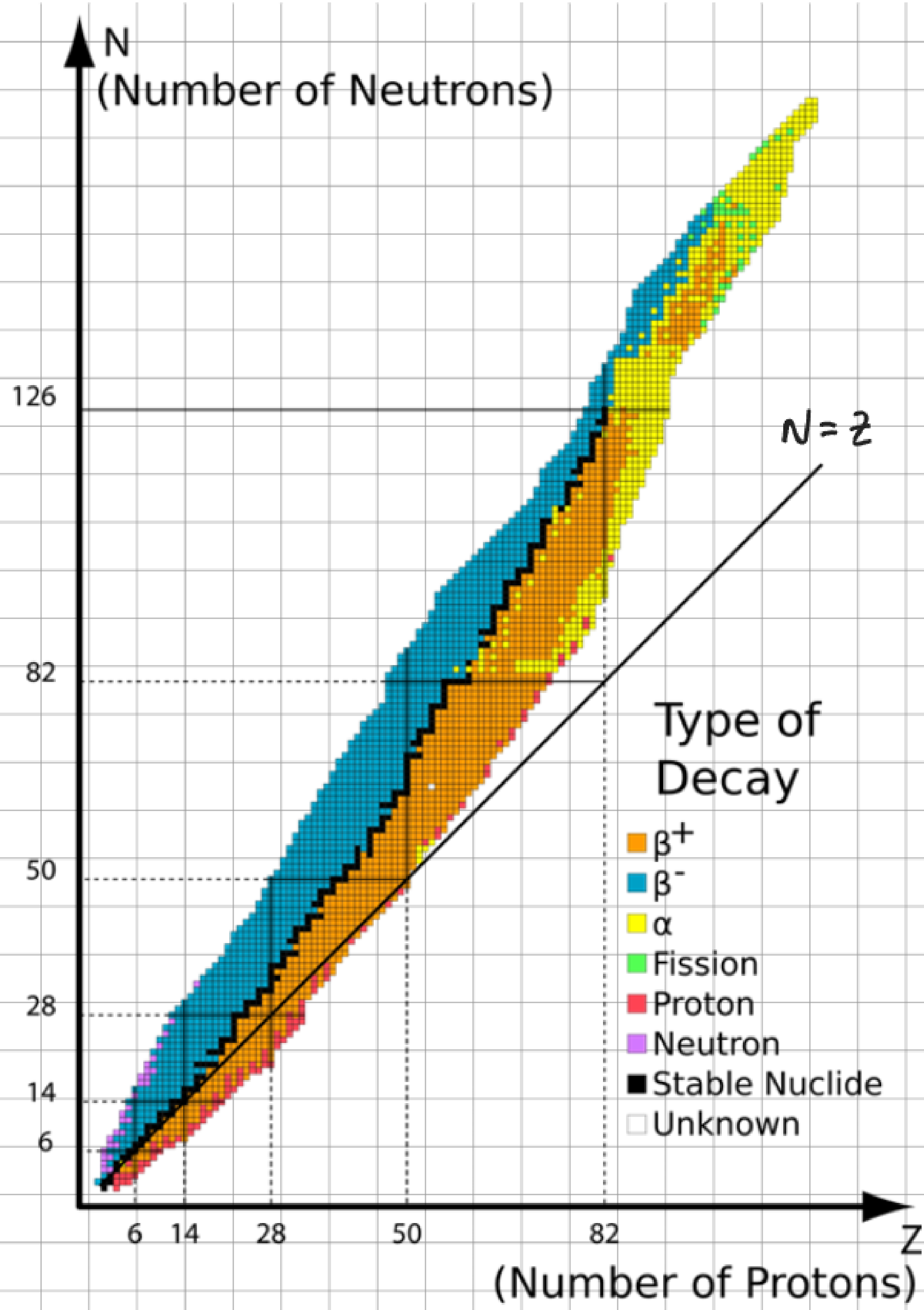
In this mode a proton turns into a neutron emitting a positron and electron neutrino.
This occurs in PROTON RICH nuclei.

$$p \longrightarrow n + e^{+} + \nu_e$$

$$^{15}_{8}O \longrightarrow {}^{15}_{7}N + {}^{0}_{+1}\beta + {}^{0}_{0}\nu_e$$

Stability

The central curve represent all 'stable' nuclei. This is when the strong interaction and electromagnetic interaction are 'balanced'. Unstable nuclei tend towards the line as they decay.



Nucleon emissions

Occasionally a nucleus will decay by simply emitting a nucleon.

$$^{5}_{3}Li \longrightarrow {}^{4}_{2}He + {}^{1}_{1}P$$

$$^{5}_{2}He \longrightarrow {}^{4}_{2}He + {}^{1}_{0}n$$