What is Ionising Radiation?

James Gray
University RPA

***Radioactivity* - a natural and spontaneous process by which the *unstable* atoms of an element emit or radiate excess energy in the form of particles or waves.**

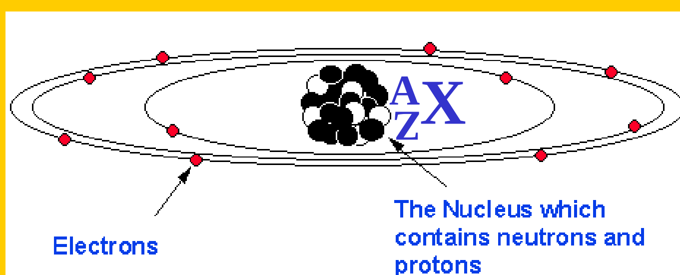
After emission the remaining *daughter* atom can either be a lower energy form of the same element *or* a completely different element.

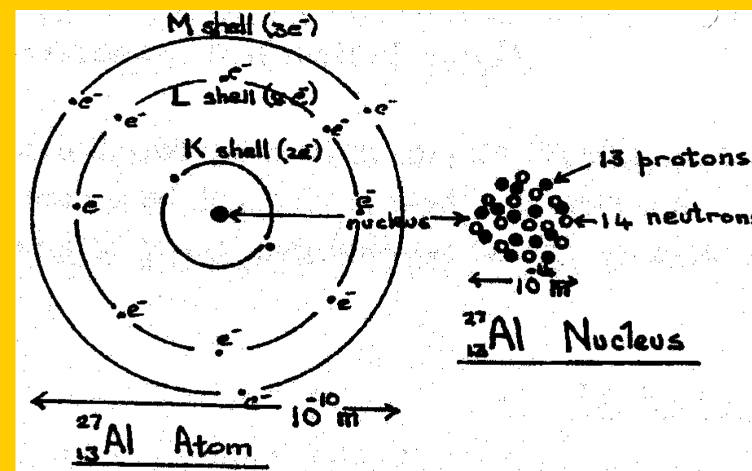
The emitted particles or waves are called *ionising radiation* because they have the ability to remove *electrons* from the atoms of any matter they interact with.

Review of Atomic Structure – 'High School' Physics

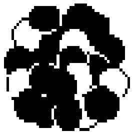
1885-1962

The Bohr Model (1913) – negatively charged electrons orbiting a positively charged nucleus. Electrons only in 'allowable' orbits.





- **Only works for hydrogen atom**
- **electrons are not 'point like' particles**
- **electrons do not 'orbit' the nucleus in a traditional sense**
- **electrons carry one unit of (-ve) electrical charge**



Nucleus, containing protons and neutrons

The Nucleus:

Two particles: protons & neutrons (hadrons)

Proton mass = 1.673 x10^{-27} kg = 1.00728 amu

Neutron mass = 1.675 x10^{-27} kg = 1.00866 amu

amu = atomic mass unit, defined relative to carbon 12

Charge: protons carry one (+ ve) unit of electrical charge
neutrons are chargeless

Forces: electrical – protons *repel* each other – *infinite range*

strong nuclear – short range (~10^{-15}m) *attractive* force

between quarks – is 137x stronger than electrical forces

the nucleus is held together by a *balance* of these forces

when the nucleus is in balance it is called *stable*

the key to the balance is the neutron: proton ratio

Summary:

- Size of atom 10^{-10}m, size of nucleus 10^{-15}m
- Made up from 3 particles – proton, neutron, electron
- Electrons exist outside of nucleus in discrete allowable orbits
- Electrons can move between orbits by absorbing/emitting energy
- Electrons carry one unit of electrical charge (-ve)
- Protons and neutrons exist within the nucleus
- They have roughly the same mass
- Protons carry one unit of electrical charge (+), neutron has no charge
- Stable nucleus there is a balance between SNF and electrical force
- When the balance is upset the nucleus is unstable

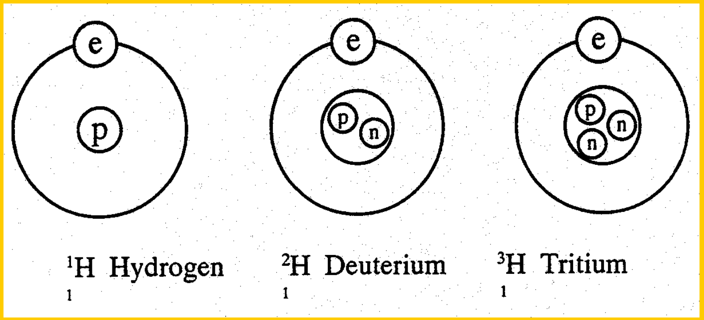
Definition:

Atoms with the same number of protons/electrons have the same physical and chemical properties, these are called *elements* e.g. all oxygen atoms have 8 protons.

Elements are arranged in order of increasing proton number and are characterised with the symbol $^{A}_{Z}X$ - Periodic Table

Elements *can* have different numbers of neutrons and these are called *isotopes*

Isotopes can be stable or *unstable*



***Isotope* - atoms of the same element with different numbers of neutrons.**

Isotopes of Hydrogen

Hydrogen - 1 proton + 1 electron - *stable*

Deuterium - 1 proton + 1 neutron + 1 electron - *stable*

Tritium - 1 proton + 2 neutrons + 1 electron - *unstable*

***Stability* - related to n:p ratio**

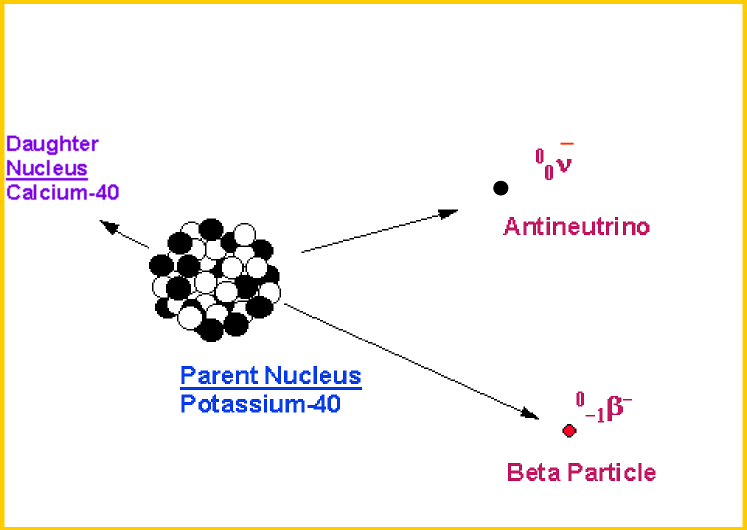
***low atomic number* - n:p ~ 1:1**

***high atomic number* - n:p rises to ~ 1.6:1**

Stability regained by radioactive decay processes

Radioactive decay processes.

1. Beta (minus) decay



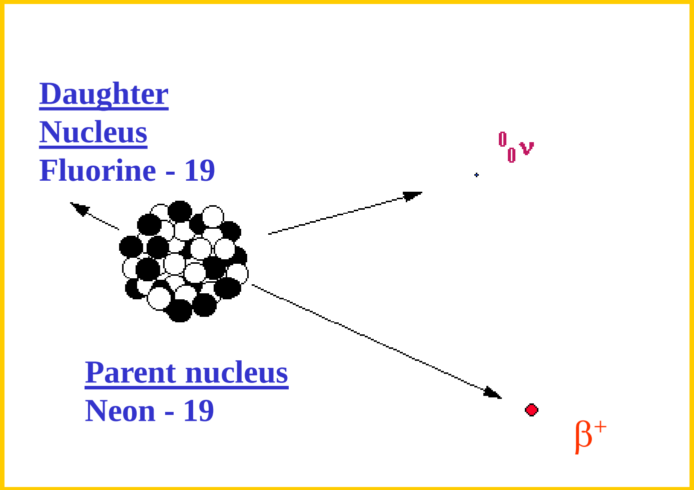
$$^{40}_{19}K \rightarrow ^{40}_{20}Ca + 1.32\,MeV\ \beta^- \max$$

General equation for beta minus decay:

$$^{A}_{Z}X \rightarrow ^{A}_{Z+1}Y + \beta^- + \bar{\upsilon}$$

Radioactive decay processes.

2. Beta (plus) decay



$$^{19}_{10}Ne \rightarrow ^{19}_{9}F + 2.22 MeV \ \beta^+ + \upsilon$$

+ annihilation radiation

General equation for beta plus decay:

$$^{A}_{Z}X \rightarrow {}_{Z-1}^{A}Y + \beta^+ + \upsilon$$

annihilation radiation = $m_e c^2$ = 0.511 MeV (x2)

Radioactive decay processes.

3. Electron capture: ➡

Excess of protons, stability reached by different process than β^+

Orbital electron is *captured* by the nucleus, neutrino emitted.

<u>Commonly</u> nucleus is left in an 'excited' state and returns to its ground state by emitting a gamma-ray photon from the *nucleus*

***In all cases* a characteristic X-ray photon is emitted by the *atom*.**

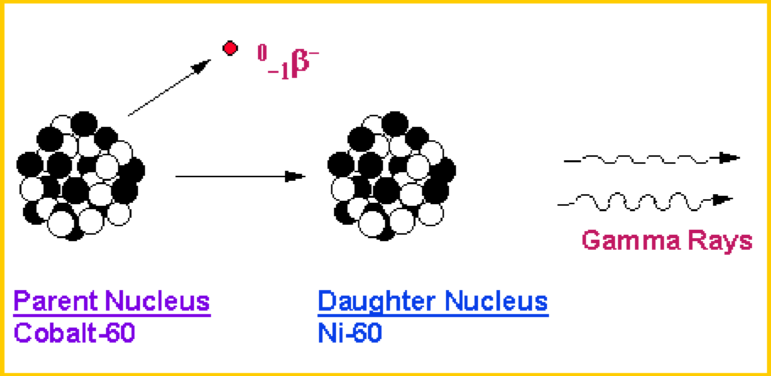
The general equation for the electron capture process is:

$$ {}^{A}_{Z}X + e \rightarrow {}^{A}_{Z-1}Y + \upsilon + X - rays + \gamma - rays\ (possibly\ ) $$

$$ {}^{125}_{53}I + e \rightarrow {}^{125}_{52}Te + Tellurium \quad X - rays\,(0.027\,Mev) + 0.035\ MeV\ \gamma - rays $$

Radioactive decay processes.

4. Gamma decay:



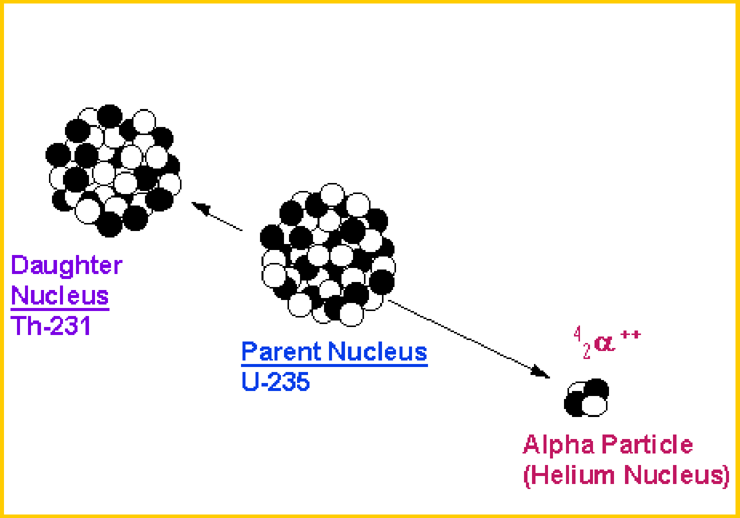
$$^{60}Co_{27} \longrightarrow {}^{60}Ni_{28} + 0.318\ \text{MeV}\ \beta^- + 1.17\ \text{MeV}\ \gamma + 1.33\ \text{MeV}\ \gamma$$

Nucleons have quantised energy levels - emitted γ-ray photons from a particular nucleus have a unique γ-ray spectrum.

γ-ray spectrum can be used to identify unknown isotopes and calibrate instruments.

Radioactive decay processes.

5. Alpha decay:



Nuclides with Z > 82

α particle = $^4He_2$ (helium nucleus) and are monoenergetic

Decay chain:

Generally, unstable heavy elements require a series of alpha and beta decays until a lighter more stable element is reached

Radioactive decay processes.

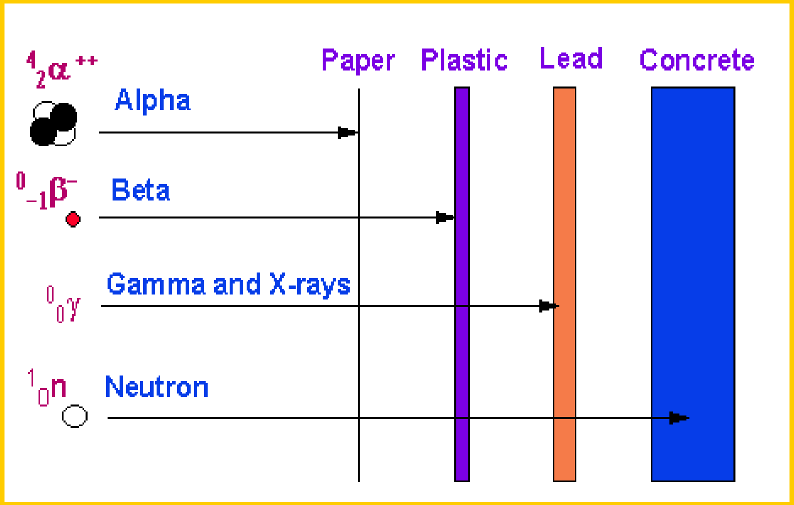
6. Neutron emission is produced by three methods:

- **Nuclear fission**
- **Deuterium bombardment of a tritium target**
- **Bombarding beryllium target with alpha particles**

X-ray Generation:

- ‘Characteristic’ X-ray emission
- Bremsstrahlung
- Man made

Penetrating Distances



α < 4cm air, will not penetrate skin.

β - several mtrs in air, penetrates skin ~ 0.8 cm, use ~ 6 mm plastic shielding.

X - penetrating, speak of half-thickness $\tau_{1/2}$, use lead shielding.

γ - more penetrating than X-rays, use lead or concrete shielding.

Activity and half-life

A radioactive nuclide decays at a rate proportional to the number of original nucleii present:

$$\frac{dN}{dt} = -\lambda N$$

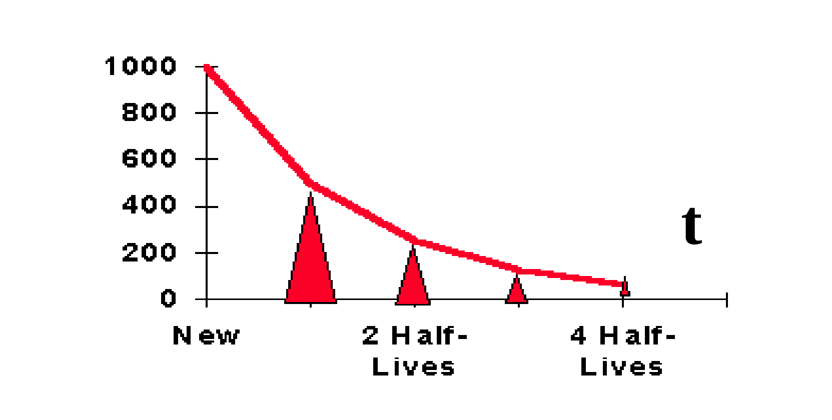
:where λ = decay constant

Integrating the above gives the decay equation:

$$N_t = N_0 e^{-\lambda t}$$

$e^{-\lambda t}$ term indicates that radioactive atoms decay exponentially

N



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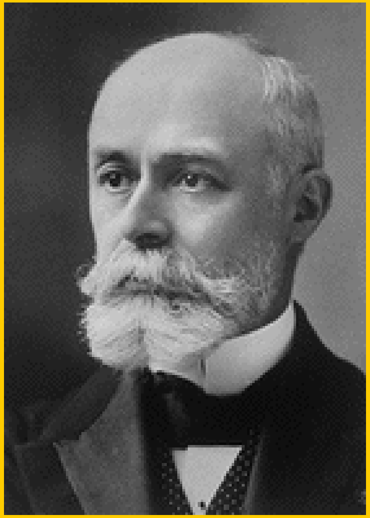
Half life ($\tau_{1/2}$): The time required for amount of radioactive material to decrease by one-half:

$$\tau_{\frac{1}{2}} = \frac{0.693}{\lambda}$$

Units:

The disintegration rate of a radioactive nuclide is called its *Activity*.

The unit of activity is the becquerel named after the discoverer of radioactivity.



ANTOINE HENRI BECQUEREL

1852-1908

1 Bq = 1 disintegration per second

this is a small unit, activity more usually measured in:

kilobecquerel (kBq)	= 10^3 Bq
Megabecquerel (MBq)	= 10^6 Bq
Gigabecquerel (GBq)	= 10^9 Bq
Terabecquerel (TBq)	= 10^{12} Bq

Units:

Old units still in use:

Curie (Ci) = 3.7 x 10^{10} disintegration per second therefore:

1 Ci	**= 3.7 x 10^{10} Bq = 37 GBq**
1 mCi	**= 3.7 x 10^{7} Bq = 37 MBq**
1 μCi	**= 3.7 x 10^{4} Bq = 37 kBq**
1 MBq	**~ 27 μCi**

Common Isotopes Used In The Lab:

^{3}H: $\tau_{1/2}$ = 12.3 yrs, β^- emitter (19 keV, 'soft')
Cannot be detected using Geiger counter
Bremsstrahlung radiation may be significant
Shielding < 0.1 mm plastic

^{14}C: $\tau_{1/2}$ = 5730 yrs, β^- emitter (157 keV, 'soft')
Can be detected using Geiger counter
Bremsstrahlung radiation may be significant
Shielding ~ 3 mm plastic

^{32}P: $\tau_{1/2}$ = 14.3 days, β^- emitter (1.71 MeV, 'hard')
Can be detected using Geiger counter
Shielding ~ 6.3 mm plastic

^{125}I: $\tau_{1/2}$ = 60 days, X-ray emitter
Can be detected using a portable scintillation counter
Shielding ~ 1 mm lead

Interaction with Matter

α, β, γ and X-rays interact with matter in 2 major ways:

<u>Ionisation</u>: removal of an electron from an atom leaving an ion.

<u>Excitation</u>: addition of energy to the atom, giving an excited state.

Charged particles:

α-particle: 2+, 1/20 c, virtually ionises every molecule encountered.

β-particle: 1-, ~ c, ionises one in every 1000 molecules.

After each ionisation the charged particle will lose energy and will finally be 'stopped' - i.e. α + β radiation has a finite <u>range.</u>

<u>Range</u> is measured in gcm^{-2}

$R_\beta = E_\beta / 2 \; gcm^{-2}$ **&** $R_\alpha = E_\alpha / 1000 \; gcm^{-2}$

Example of a range calculation

Q. What is the range of a ^{35}S beta particle in perspex?

A. The max. energy of the ^{35}S beta particle is 0.168 MeV
∴ the range of the particle is 0.084 gcm^{-2}

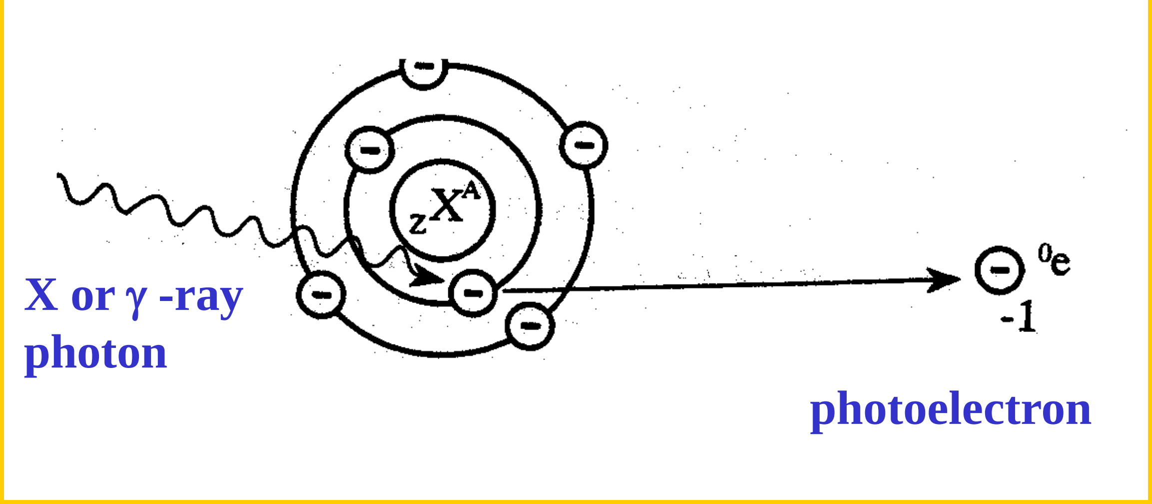
The density (ρ) of perspex = 1.2 gcm^{-3}

∴ the penetration depth in cm (t) is given by t = range / ρ

= 0.084 / 1.2 = 0.07 cm = 0.7 mm

Interaction with Matter

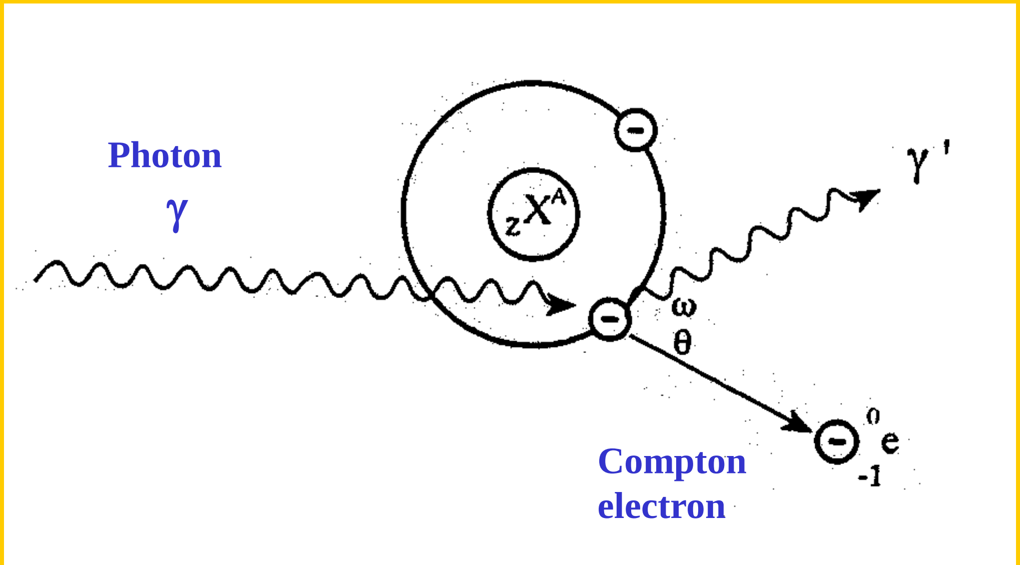
X and γ-rays: Chargeless, more penetrating than α or β. Interact via: photoelectric effect, the Compton effect and pair production.



Photoelectric Effect

Interaction with Matter

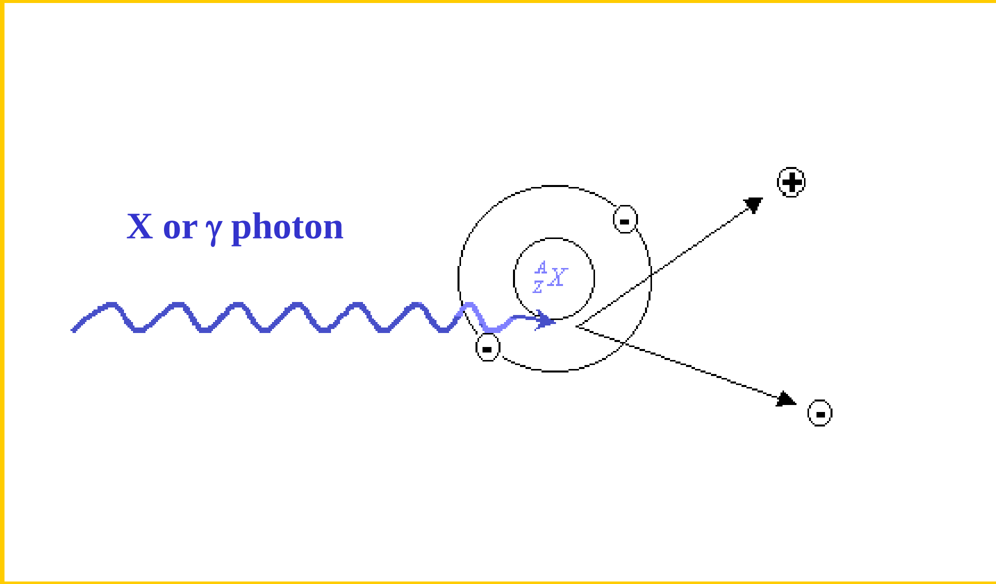
X and γ-rays: Chargeless, more penetrating than α or β. Interact via: photoelectric effect, the Compton effect and pair production.



Compton Effect

Interaction with Matter

**X and γ-rays: Chargeless, more penetrating than α or β.
Interact via: photoelectric effect, the Compton effect and pair production.**



Pair Production

Interaction with Matter

X and γ rays are types of electromagnetic radiation.

They are not ‘stopped’ by matter but are attenuated.

Attenuation depends on energy of radiation, thickness and density of absorber material.

Given thickness of absorber produces the same fractional reduction in intensity.

Analogous to half-life - called half-thickness - thickness of absorber required to reduce intensity by 1/2.

If we use three half-thickness' of absorber then this will reduce the intensity by: 1/2+1/2+1/2 = 1/8

Summary:

- **Unstable atoms (excess p or n) can regain stability by emitting radiation**
- **Two types – particle and electromagnetic**
- **Particle:** **β minus – electrons (-1 charge)**
  β plus – positrons (+1 charge)
  α – helium nuclei (+2 charge)
  neutrons (chargeless)
- **EM:** **γ – ray – originate from inside nucleus**
  X – ray – originate outside nucleus or man made
- **Shielding:** **charged particles – low density materials**
  γ/X rays – high density materials
- **Units** **Becquerel (Bq) old unit Curie (Ci)**

Excellent physics website: http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html

Common laboratory isotopes

^{32}P – pure beta (minus)

^{33}P - pure beta (minus)

^{14}C - pure beta (minus)

^{3}H - pure beta (minus)

^{35}S - pure beta (minus)

^{125}I – electron capture – gamma and X-rays

^{131}I – beta (minus) + gamma