Edexcel GCSE Physics

Topic 6: Radioactivity

Notes

(Content in bold is for Higher Tier only)

Radioactivity

Atom

- A positively charged nucleus
  - Made of positive protons
  - And neutral neutrons
- Surrounded by negatively charged electrons
  - The electrons orbit the nucleus at different fixed distances from the nucleus
- The nuclear radius is a lot smaller than the radius of the atom
- Almost all the mass of the atoms lies in the nucleus

Subatomic Particle	Relative Mass	Relative Charge
Proton	1	+1
Neutron	1	0
Electron	0.0005	-1
Positron	0.0005	+1

Size of atom: $\sim 0.1 nanometres, 10^{-10}$

Isotopes and Elements

- Atoms of the same element have the same number of protons
- Neutral atoms have the same number of electrons and protons
- Isotopes are atoms of the same element, but with different masses
  - They have the same number of protons but different number of neutrons
- For Example, Carbon-12, Carbon-13 and Carbon-14

$$^{A}_{Z}X^{\pm n}$$

- X is the letter of their element
- A is the mass number (number of neutrons and protons)
- Z is the proton number
- N is the charge
  - On a neutral atom, electrons = protons, so cancels out
  - If there are N more electrons than protons, then the charge is –N
  - If there are N fewer electrons than protons, then the charge is +N
  - The number of protons does not change for a certain element

Atoms and EM Radiation

- When electrons change orbit (move closer or further from the nucleus)
  - When electrons move to a higher orbit (further from the nucleus)
    - The atom has absorbed EM radiation
  - When the electrons falls to a lower orbit (closer to the nucleus)
    - The atoms has emitted EM radiation
- If an electron gains enough energy, it can leave the atom to form an ion

Radiation

- Decay occurs in a random process
- Forms of decay
  - **Alpha (a helium nucleus)**
    - Highly ionising
    - Weakly penetrating
  - **Beta Minus (electron)**
    - Medium ionising
    - Medium penetration
  - **Beta Plus (positron)**
    - Medium ionising
    - Medium penetration
  - **Gamma (radiation)**
    - Low ionising
    - Highly penetration
  - **Neutrons**

Background Radiation

- Weak radiation that can be detected from natural / external sources
- Examples of background radiation include:
  - Cosmic rays
  - Radiation from underground rocks
  - Nuclear fallout
  - Medical rays

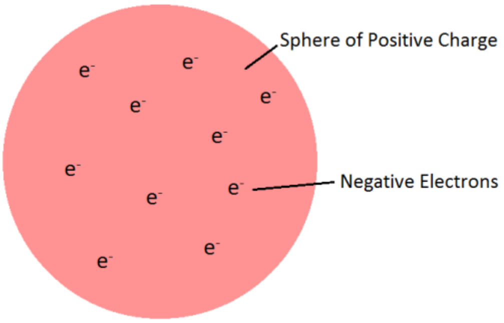
Methods of Measuring Radioactivity

- Photographic film
  - Film goes darker when it absorbs radiation – the more radiation absorbed, the darker it gets (the film is initially white)
  - Worn as badges by people who work with radiation, to check how much exposure they have had
- Geiger-Muller Tube
  - A tube which can detect radiation
  - Each time it absorbs radiation, it transmits an electrical pulse to the machine, which produces a clicking sound
    - The greater the number of clicks per second (the frequency of clicks) the more radiation is present

Atomic Structure

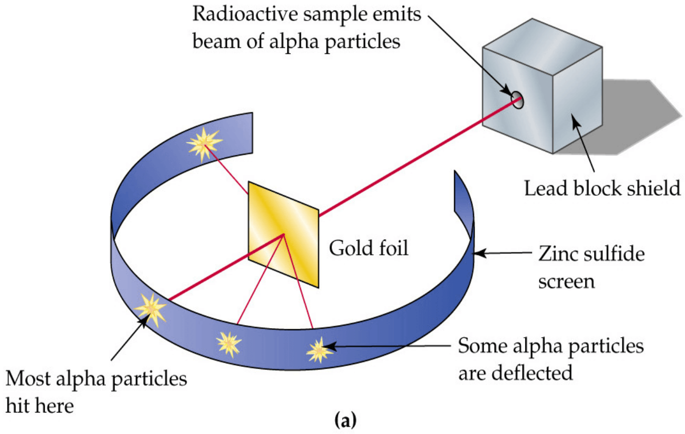
How and why the atomic model has changed over time

1800 - Dalton said everything was made of atoms
1897 - JJ Thomson discovered the electron
The Plum Pudding Model was formed



The overall charge of an atom is neutral, so the negative electrons were dispersed through the positive "pudding" to cancel out the charges.

1911 - Rutherford realised most of the atom was empty space
The Gold Foil Experiment



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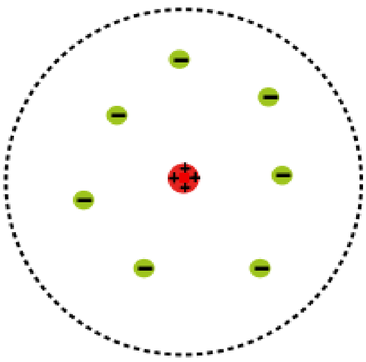
Most particles went straight through
- So most of atom is empty space

Some α particles were slightly deflected
- So nucleus must be positive, repelling positive α

Few α particles were deflected by >90°
- So nucleus contained most of the mass

This experiment was carried out by Geiger and Marsden

1913 - Rutherford Model



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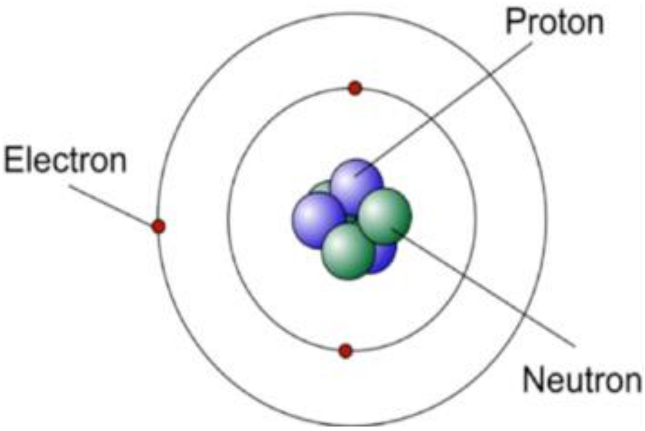
Now there is a positive nucleus at the centre of the atom, and negative electrons existing in a cloud around the nucleus

1913 – Bohr produced the final model of the atom



If Rutherford was right, the electrons in the cloud close to the nucleus would get attracted and cause the atom to collapse. therefore, he concluded that the electrons exist in fixed 'orbitals'

Decay Processes

- Beta-Minus Decay
    - Neutron becomes a proton, and releases an electron
- Beta-Plus Decay
    - Proton becomes a neutron, and releases a positron

$$^{A}_{Z}X \rightarrow\ ^{A\prime}_{Z\prime}Y + decay\ particle$$

Alpha

An alpha particle is equivalent to a helium nucleus.

$$^{A}_{Z}X \rightarrow\ ^{A-4}_{Z-2}Y + \,^{4}_{2}\alpha$$

Beta

A beta particle is an electron emitted from the nucleus

$$^{A}_{Z}X \rightarrow\ _{Z+1}{}^{A}Y + \,_{-1}^{\ 0}e^{-}\ (+\overline{v_e})$$

Gamma

A gamma ray is electromagnetic radiation

$$^{A}_{Z}X \rightarrow\ ^{A\prime}_{Z\prime}Y + \gamma$$

Nuclei *after* decay often have excess energy, which they release as gamma when the atom undergoes nuclear arrangement.

Activity

- Activity is the number of decays in a sample per second
- Activity is initially very high (the more atoms in the sample, the greater the chance of at least one of them will decay
    - Activity decreases exponentially over time
- Units of Activity are Becquerel, Bq

Half Life

- The half-life of an isotope is the time taken for half the nuclei in a sample to decay
    - Or the time taken for the activity of a sample to decay by half

- It cannot be predicted when any one nucleus will decay, but the half-life is a constant that enables the activity of a very large number of nuclei to be predicted during the decay

Net Decline

- **Work out ratio of net decline of radioactive nuclei after X half-lives**
    - **Half the initial number of nuclei, and keep doing so X number of times**
    - $\textbf{net decline} = \dfrac{\textbf{initial number} - \textbf{number after X half lives}}{\textbf{initial number}}$

Example:

There were initially 80 nuclei, with a half-life of 15 minutes, net decline after 3 half-lives?

- $\mathbf{80 \rightarrow 40 \rightarrow 20 \rightarrow 10}$
- $\mathbf{1^{st} \mathit{life},\ \ 2^{nd},\ \ 3^{rd}}$ **half-life**
- $\boldsymbol{so\ net\ decline} = \dfrac{\mathbf{80-10}}{\mathbf{80}} = \dfrac{\mathbf{7}}{\mathbf{8}}$

Uses of Radioactivity (Physics Only)

- Smoke Alarms
    - Americium is used in smoke alarms
    - Americium has a half-life of 432 years
        - It is an alpha emitter
    - This is stopped by a few centimetres of air (as it is weakly penetrating)
    - The alpha particles ionise air particles and makes them charged therefore making a current
    - If smoke enters the air around the alarm, the current drops in the circuit
        - Causing the alarm to sound
- Irradiating food
    - Gamma rays transfer energy to bacteria, killing them and sterilising food
    - Also used to delay ripening of fruit
- Sterilisation of equipment
    - Radiation, usually gamma, exposed onto equipment to kill all microbes present on the equipment, so they are safe for operations
- Tracing and Gauging Thickness
    - Beta radiation is mildly penetrating, and can just pass through paper
    - A source and receiver are placed either side of the paper during its production
        - If there is a drop or rise in received electrons, then that means the thickness of the paper has changed – i.e. a defect in the production
    - It is also used inside pipes, with a detector placed externally, to measure the thickness of walls of the pipe
- Diagnosis and Treatment of cancer
    - Consuming/injecting a gamma emitter, it passes through the body and an external detector can picture where the tracer has collected in the body, which can reveal tumours
    - Gamma rays are used on the tumour, killing the cancer cells
    - However, exposing rays on healthy cells cause them to possibly mutate or causes damage (see next section)

Dangers of ionising radiation (Physics Only)

- A short half-life
    - The source presents less of a risk, as it does not remain strongly radioactive

    - This means initially it is very radioactive, but quickly dies down
    - So presents less of a long-term risk
- Long half-life
    - The source remains weakly radioactive for a long period of time
    - Americium is suitable in smoke alarms because it will not need to be replenished, and its weak activity means it won't be harmful to anyone
        - Its half-life is 432 years

Safety Measures

- Limiting patient dose
    - Only use radioactive tracers with a short enough half life
        - So short enough to quickly be removed over a day or so
        - But long enough to still be detectable after the time taken for it to pass through the body
        - Common medical tracers used have a half-life of 6hrs
- Limiting risks to medical personnel
    - They leave the room during radioactive tests, as their everyday close proximity to the radioactive sources puts their health at risk in the long-term

Difference in Radiation

- Contamination
    - Lasts for a long period of time
    - The source of the radiation is transferred to an object
    - E.g. radioactive dust settling on your skin (your skin becomes contaminated)
- Irradiation
    - Lasts only for a short period of time
    - The source emits radiation, which reaches the object
    - E.g. Radioactive dust emitting beta radiation, which "irradiates" your skin
    - Medical items are irradiated sometimes to kill bacteria on its surface, but not to make the medical tools themselves radioactive

Treatment of Tumours (Physics Only)

- External
    - A beam of gamma radiation (usually a wide beam) rotates around the body
    - It continually focuses on the tumour, while only passing momentarily across healthy cells surrounding the tumour
    - This ensures minimal damage occurs on the healthy cells, while the tumour is most affected
        - However it takes a long time to fully treat the tumour, taking multiple visits for around 5 weeks
        - There is a greater risk of long-term side effects, as the radiation passes through healthy tissues
- Internal
    - Radioactive material is held within a needle, and is injected directly into the tumour
        - A longer period of time needs to be spent in hospital, as some radioactive implants are of high radioactivity (so you emit radiation, requiring you to have very limited contact with visitors until the source's activity has decreased)

PET Scanners (Physics Only)

- Positron emission tomography
    - Radioactive tracer is inserted into the body

        - The tracer is tagged to the desired chemical, and the tracer therefore travels in the body where this certain chemical travels (e.g. glucose or ammonia)
    - The scanner records where the tracer emits radiation
    - This produces a live 3D visualisation of the body
        - Used to show how effective current treatment is
        - Or to diagnose cancer, epilepsy, Alzheimer's

Isotopes (Physics Only)

- The isotope used in PET scanners is made locally just before insertion
- This is because the tracer has a half-life of 110mins, so it cannot be stored for long before it decays

Nuclear Power (Physics Only)

- Uranium fuel splits releasing neutrons, which are absorbed by further uranium nuclei, which split (this is fission, in a chain reaction)
- No carbon dioxide is produced
- There is a safety risk of radiation leaking, or the chain reaction become uncontrollable and causing a meltdown
- Also, a security risks as terrorists can try and obtain the radioactive material
- Public perception of nuclear power is negative, due to the fatal disasters caused by nuclear power plants
- Waste disposal is difficult – initially extremely hot, the waste needs to be placed deep in lakes, 'cooling ponds' to cool down, before being stored deep underground (it can be used for nuclear warheads so is a terrorist risk) for centuries

Nuclear Energy (Physics Only)

- Fusion is the process of small nuclei being forced together (under immense temperature and pressure) to form a heavier nucleus
    - This is the energy source for stars
    - The electrostatic repulsion of the protons in the two different nuclei means a lot of energy is required to bring the nuclei close enough to fuse
        - So fusion cannot happen at low temperatures and pressures
        - So this makes it very difficult to make a practical and economic fusion power station
- Fission is the process of a nucleus splitting into two smaller nuclei after absorbing neutrons, which releases more neutrons
- Radioactive Decay is when an unstable nucleus decays into two smaller nuclei
- All these process release energy, and can be a source of energy

U-235 Fission (Physics Only)

- Uranium-235 (this means 235 nucleons) is the fuel used in nuclear (fission) power stations
    - It absorbs neutrons, and becomes unstable
    - This causes it to undergo fission
        - Releasing energy
        - Forming two 'daughter' nuclei
            - The products are radioactive, as they are strong gamma emitters (some of the energy released from the fission is also held by the daughter nuclei)
        - Emitting two or more neutrons as well

Chain Reaction (Physics Only)

- After one nucleus splits, emitting neutrons, these neutrons cause further fissions, which releases more neutrons…. This continuous process is a chain reaction
- This needs to be controlled
    - As more neutrons are released than the number absorbed, this could cause an exponential process
        - For example the first fission releases two neutrons, which will cause 2 fissions, releasing four neutrons, causing four fissions, releasing eight neutrons… and so on, which would cause a meltdown
    - Moderators
        - This is usually water/graphite, and slows down the emitted neutrons to be absorbed for further fissions (fast moving neutrons cannot be easily absorbed)
    - Control Rods
        - These are boron rods in the reactor core, which absorb excess neutrons, preventing a runaway chain reaction
- The heat energy from the chain reaction is absorbed by water (coolant) which evaporates into steam, and is used to turn a turbine, which turns the generator which generates electricity