Nuclear Radiation

Atomic Structure

All atoms consist of a central **nucleus**. This contains **positively charged protons** and **neutral neutrons**. **Negatively charged electrons** orbit the nucleus.

Nuclear Radiation

Nuclear radiation gets its name from where it comes from. All nuclear radiation originates from the nuclei of unstable atoms. There are 3 types of nuclear radiation.

Name	Symbol	Charge	Ionisation	Nature
alpha particle	α	+2	large	2 protons, 2 neutrons (Helium nucleus)
beta particle	β	-1	small	fast moving electron
gamma ray	γ	-	small	electromagnetic radiation

Ionisation

All 3 forms of nuclear radiation can cause ionisation of atoms. Ionisation is the removal (or sometimes addition) of electrons from an atom. This causes a neutral atom to become positively (or negatively) charged. A charged atom is called an ion.

This change in nature of the atom can lead to a change in nature of molecules too. Most importantly this can lead to the damaging of DNA causing cell mutation or even cell death. Adequate precautions must be taken when working with any type of radioactive materials.

It is the ionising property of nuclear radiation that makes it both useful in the treatment of cancerous tissues but also a hazard if exposure is not regulated properly.

Nuclide Notation

Nuclide notation is used to briefly describe the structure of the nuclei that we are dealing with.

Mass Number
(protons + neutrons)

$$^{238}_{92}\mathrm{U}$$

Element symbol
(defined by atomic number)

Atomic Number
(protons)

Alpha Decay

Alpha decay is when an unstable nucleus emits an alpha particle. This changes the nature of the original atom:

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

Here Uranium-238 has become Thorium-234, emitting an alpha particle (identical in nature to a helium nucleus)

Beta Decay

Beta decay is when an unstable nucleus emits a beta particle.

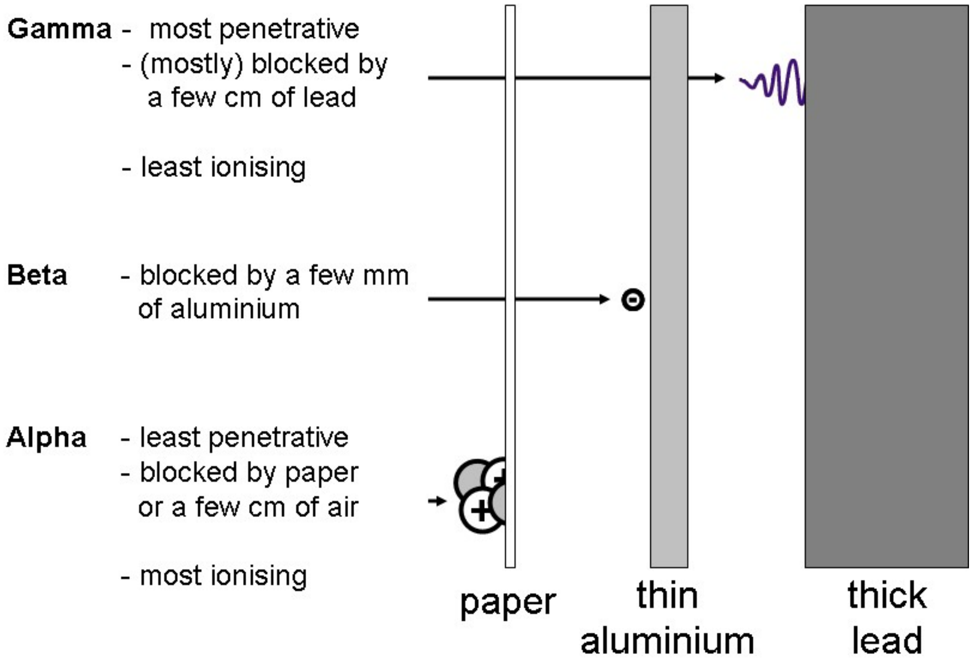
$$^{234}_{90}Th \rightarrow \, ^{234}_{91}Pa + \, ^{0}_{-1}e$$

Here Thorium-234 has become Protactinium-234, emitting an beta particle (identical in nature to a fast moving electron)

Gamma Decay

Gamma decay is when an unstable nucleus emits a gamma ray. There is no change in the number of protons or neutrons and so the element remains the same as before.

Properties of Alpha, Beta and Gamma



Sources of Background Radiation

Cosmic rays	Radiation that reaches the Earth from outer space
Living Things	All animals and plants emit natural levels of radiation
Rocks	Some rocks give off radioactive radon gas
Soil and plants	Radioactive materials from rocks in the ground are absorbed by the soil and hence passed on to plants

Measuring Radiation

Activity

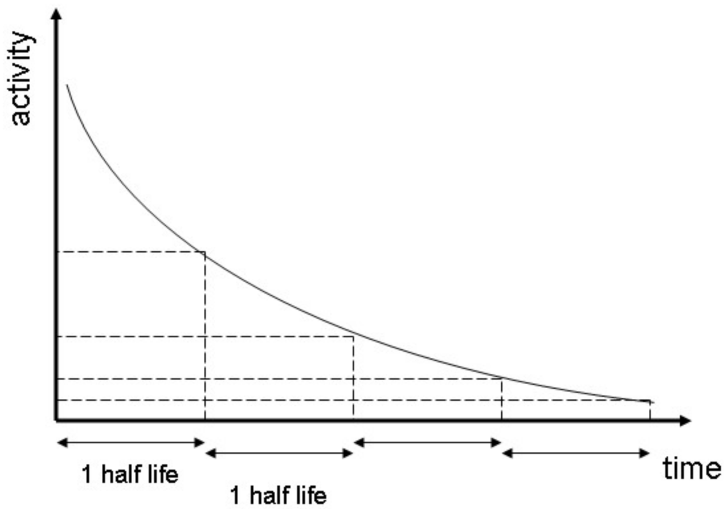
Activity is the number of nuclei in a substance which decay each second. This count can be measured using a Geiger tube and counter. It is calculated using the following equation:

$$\text{activity} = \frac{\text{number of decays}}{\text{time}} \qquad \boxed{A = \frac{N}{t}}$$

activity is measured in becquerels (Bq)
number has no units
time is measure in seconds (s)

Half Life

The activity of a radioactive substance decreases with time. The activity will drop by half its original value in a specific period of time, this time is known as the **half life** of a substance. This value is a constant for a specific substance and is different for different substances.



Absorbed Dose

Absorbed dose measures the amount of energy a given mass of tissue is exposed to.

$$\text{absorbed dose} = \frac{\text{energy absorbed}}{\text{mass of tissue}} \qquad \boxed{D = \frac{E}{m}}$$

absorbed dose is measured in grays (Gy)
energy absorbed is measured in joules (J)
mass of tissue is measured in kilograms (kg)

Equivalent Dose and Weighting Factor

Equivalent dose takes into account the type of radiation.

$$\text{Equivalent Dose} = \text{Absorbed Dose} \times \text{Weighting Factor} \qquad \boxed{H = Dw_R}$$

equivalent dose, H, is measured in seiverts, Sv
absorbed dose, D, is measured in grays, Gy
weighting factor has no units

Type of radiation	**Radiation weighting factor**
Alpha	20
Beta	1
Fast neutrons	10
Gamma	1
Slow neutrons	3

Factors affecting Biological Risk

The potential for biological damage to tissue is determined by several factors:

- duration of exposure
- distance from source
- mass of exposed tissue
- energy absorbed
- type of radiation

Equivalent Dose Rate

Since the time over which a specific dose is received is also an important factor we can use the Equivalent Dose Rate to relate levels of exposure

$$\text{Equivalent Dose Rate} = \frac{\text{Equivalent Dose}}{\text{time}} \qquad \boxed{\dot{H} = \frac{H}{t}}$$

Equivalent Dose Rate can often be represented using different units. The standard is seiverts per second, however depending on the units used in the example and equation it could be given as any of the following:

Equivalent Dose Rate units	Equivalent Dose units	Time units
Sv s^{-1}	seiverts	seconds
μSv s^{-1}	micro seiverts	seconds
mSv m^{-1}	milli seiverts	minutes
Sv h^{-1}	seiverts	hours
Sv y^{-1}	seiverts	years

(other unit combinations are also possible)

Comparison of Equivalent Dose (gov.uk)

Source of exposure	**Dose**
Dental x-ray	0.005 mSv
100g of Brazil nuts	0.01 mSv
Chest x-ray	0.014 mSv
Transatlantic flight	0.08 mSv
Nuclear power station worker average annual occupational exposure (2010)	0.18 mSv
UK annual average radon dose	1.3 mSv
CT scan of the head	1.4 mSv
UK average annual radiation dose	2.7 mSv
USA average annual radiation dose	6.2 mSv
CT scan of the chest	6.6 mSv
Average annual radon dose to people in Cornwall	6.9 mSv
CT scan of the whole spine	10 mSv
Annual exposure limit for nuclear industry employees	20 mSv
Level at which changes in blood cells can be readily observed	100 mSv
Acute radiation effects including nausea and a reduction in white blood cell count	1000 mSv
Dose of radiation which would kill about half of those receiving it in a month	5000 mSv

Below are the equivalent dose rate and exposure safety limits for the public and for workers in the radiation industries in terms of annual effective equivalent dose (SQA)

Average annual background radiation in the UK	2.2 mSv
Annual effective dose limit for member of the public	1.0 mSv
Annual effective dose limit for radiation worker	20 mSV

Applications of Nuclear Radiation

Besides the generation of energy and electricity, nuclear physics provides many applications. These tend to be based on the properties of the ionising radiation that is produced. Some examples include:

Radiotherapy	Using directed ionising radiation to damage the cancerous cells that make up tumours. Damaged cells die off and tumours can be decreased in size as a result. Naturally this presents hazards to healthy cells too.
Carbon Dating	Carbon-14 is radioactive. All living things contain carbon. By looking at the activity of a carbon source we can determine its age.
Detecting Faults	Penetrative gamma rays will highlight structural weaknesses in materials. Thin or cracked areas will allow more gamma rays to pass through and, if they are detected on the other side, the damaged area can be identified.
Smoke Detectors	These use a radioactive isotope which emits alpha particles. If smoke blocks them from reaching a sensor then an alarm will sound.
Sterilisation	Germs and bacteria can be killed by the ionising effects of radiation, sterilising equipment
Medical Tracing	When placed inside the body, gamma ray sources can be follow to detect blockages or any other abnormalities.
Nuclear Energy	This does not make use of nuclear radiation itself, but involves the splitting or fusing of atomic nuclei (plural for nucleus) in order to release energy (as heat) for the generation of electricity (see fission and fusion below)

Nuclear Energy

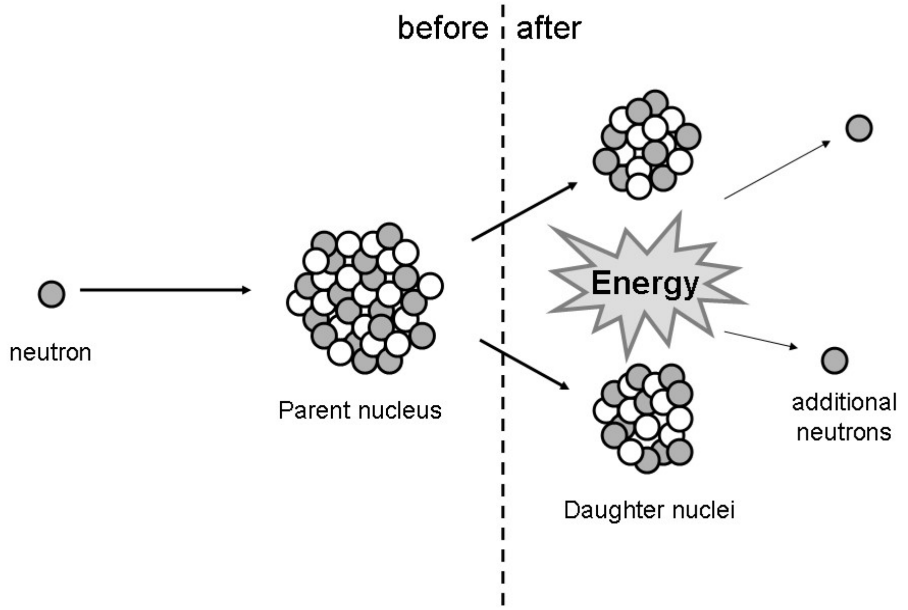
Definitions

There are two ways of generating energy through a nuclear process.

Fission - from fissure, to split
- taking massive atoms and splitting them, producing lighter elements
- Fission is currently used for electricity generation

Fusion - to fuse together
- combining atomic nuclei of small mass and producing heavier elements
- Fusion, takes place in the Sun

Nuclear Fission

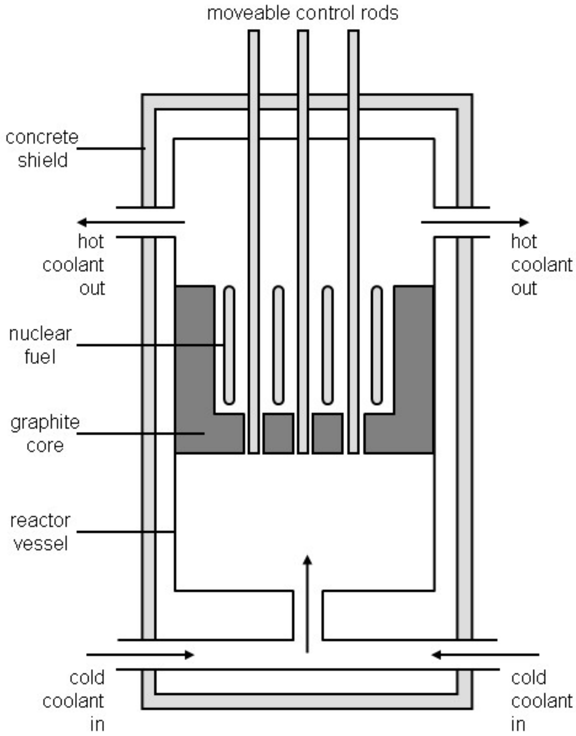


A neutron is fired at the nucleus of a "heavy" element. The nucleus becomes unstable and splits into two smaller daughter nuclei. The result is an overall decrease in mass and a release of energy (as kinetic energy in the particles, which we interpret as heat energy).

Nuclear Chain reaction

Additional neutrons are also produced which can go on to initiate further reactions. This effect is known as chain (or cascade) reaction. Such a reaction will be able to sustain itself, however can grow out of control. This could lead to a meltdown and so control rods are used to control/reduce the rate of the reaction.

Shielding and Cooling of Reactors



nuclear fuel - where the reaction takes place

graphite core - main reaction rate control

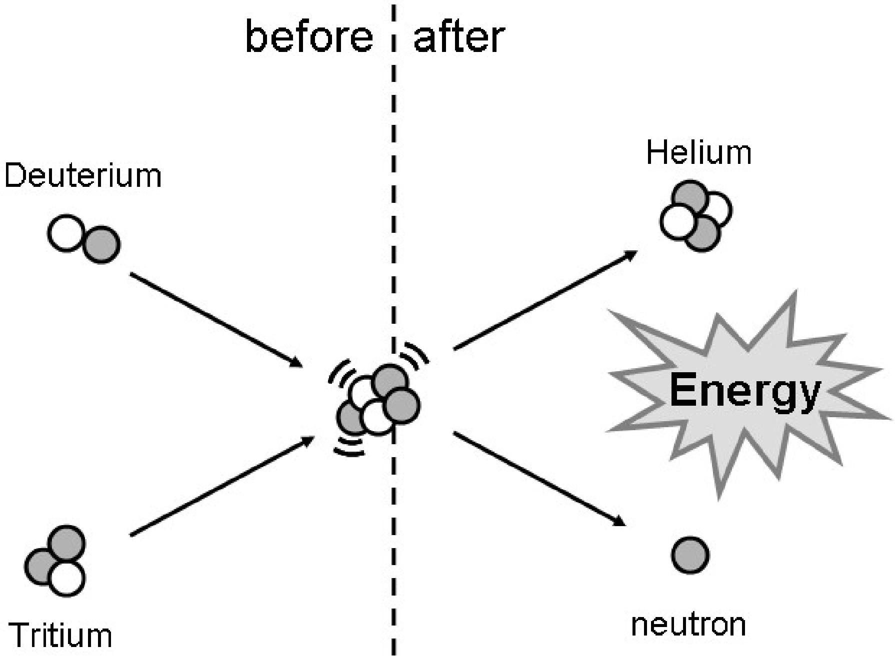
control rods - control the rate of the nuclear reaction by absorbing neutrons when inserted

concrete shield - outermost containment preventing the release of radioactive material into the environment

reactor vessel - innermost containment preventing the release of radioactive material into the environment

liquid coolant - maintains a safe operating temperature for the reactor

Nuclear Fusion



If Deuterium and Tritium (2 forms of heavy hydrogen) are combined under the right conditions they fuse together to create the element helium. Again, there is a decrease in overall mass and so a release of energy (kinetic energy of particles, interpreted as heat). The matter involved must be at a high temperature and pressure (like the core of the Sun) for this reaction to occur. The particles are charged and so strong magnetic fields are used to contain and control the reaction.