Nuclear chemistry

Radioactivity, radioactive isotopes, nuclear energy, radioactive decay

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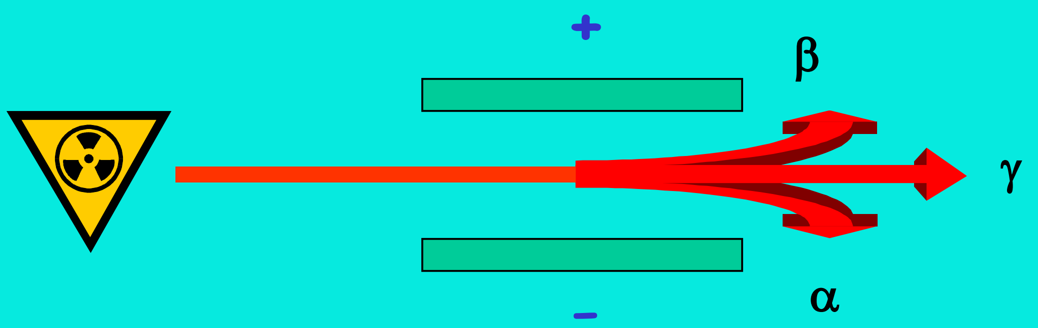
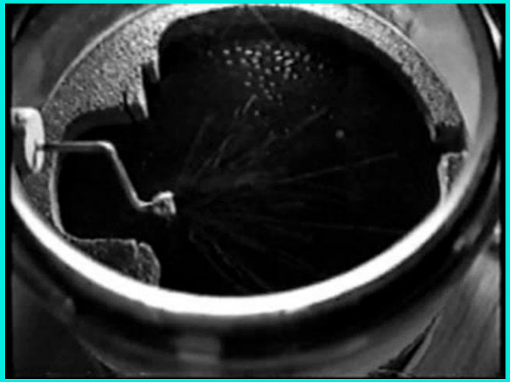
Radioactivity, properties

The nucleus of an atom contains positive protons and neutral neutrons. (except hydrogen). The stability of the nucleus depends on the ratio of neutrons to protons.
Radioactive emission of alpha or beta radiation changes this ratio.

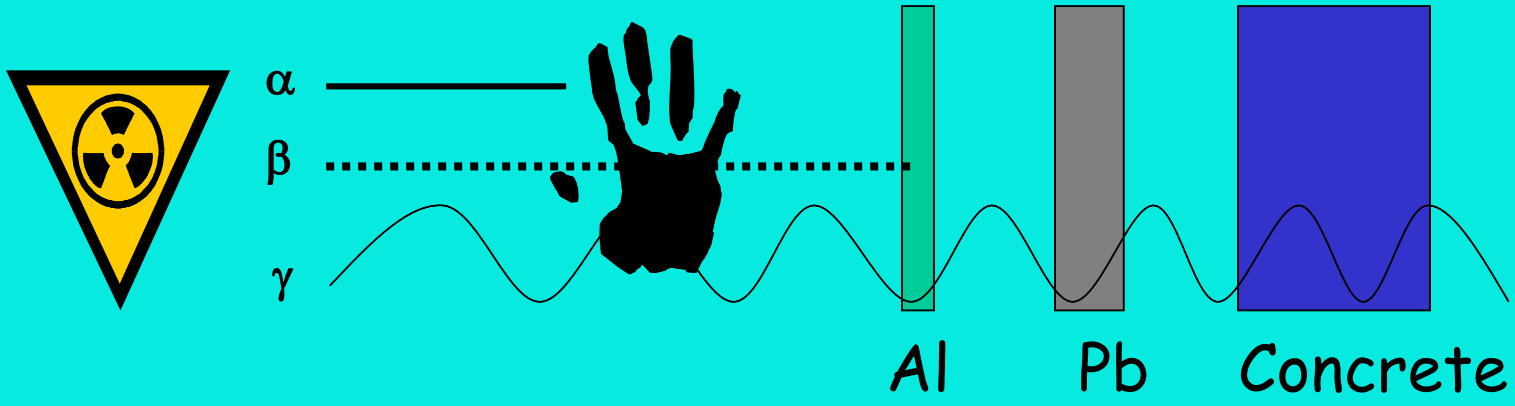
There are 3 types of radiation, alpha α, beta β and gamma γ.
Their properties can be studied using an electrical field.





α	Slow moving **positively** charged particle, attracted to the negative plate.
β	Fast moving **negatively** charged particle, attracted to the positive plate.
γ	Electromagnetic radiation (travels at speed of light). **No** deflection

Radioactivity, properties



α **Alpha** particles come from the nucleus of a radioactive atom, they consist of 2 protons and 2 neutrons, hence have a 2^+ charge. A few cm of air will stop them.

β **Beta** particles come from the nucleus of a radioactive atom, they consist of fast moving electrons hence have a 1^- charge. A few meters of air and a thin sheet of Al foil can stop them.

γ **Gamma** waves come from the nucleus of a radioactive atom, they are electromagnetic waves. Thick lead or concrete will absorb gamma rays.

Alpha radiation in more detail

Alpha radiation consists of helium nuclei, ${}^{4}_{2}He^{2+}$

When a radioactive isotope decays by alpha emission the nucleus loses 2 protons (decreasing the atomic number by 2) and two neutrons (decreasing the mass number by 4).

$$ {}^{232}_{90}\mathbf{Th} \longrightarrow {}^{228}_{88}\mathbf{Ra} + {}^{4}_{2}\mathbf{He} $$

Beta radiation in more detail

A beta particle is an electron. Since the nucleus does not contain electrons, it is thought that a beta particle is formed when a neutron splits up into a proton and an electron.

The proton stays inside the nucleus, and the electron is shot out of the nucleus as the β particle.

As the nucleus contain one less neutron and one more proton the atomic number increases by one and the mass number stays the same.

$$^{228}_{88}\mathrm{Th} \longrightarrow {}^{228}_{89}\mathrm{Ac} + {}^{0}_{-1}e$$

Changes in the nucleus

How does the nucleus changes with radioactive decay?
Notice how the mass and atomic change.

Alpha (α) $^{A}_{Z}X \longrightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He^{2+}$

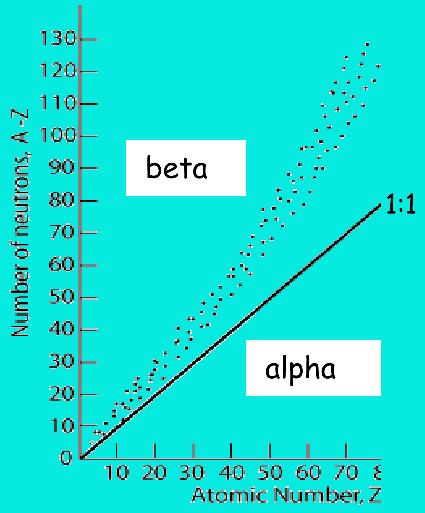
With an alpha particle 2 protons + 2 neutrons are emitted

Beta (β) $^{A}_{Z}X \longrightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}e$

With beta a neutron ➔ proton (is gained) + electron

There are 55 radioisotopes in nature (radioactive isotopes).
Artificial radioactive isotopes are made inside nuclear reactors.

Radioactivity



Elements can exist in more than one form.
An **isotope** is an element with the same atomic number but a different mass number.

The **stability** of an element's nucleus depends upon the **ratio of neutrons to protons**, for smaller elements a Neutron : proton ratio of about **1:1** is required for a stable nucleus. A greater number of neutrons results in alpha emission.
For larger (and heavier) atoms it is a neutron : proton ratio of about **1.5 : 1** is needed to provide stability.

Background radiation:
The natural level of radioactivity in the environment.

Radioactive Decay

A measure of how quickly a radioactive substances decays is called it's **half life**. Atomic nuclei are said to be unstable when they spontaneously disintegrate. It is impossible to predict when a particular atom will disintegrate. It is a random process.

The half life ($t_{1/2}$) of a radioactive isotope is the time taken for the mass or activity of the isotope to halve by radioactive decay.
The half life is independent of mass, pressure, concentration or the chemical state of the isotope

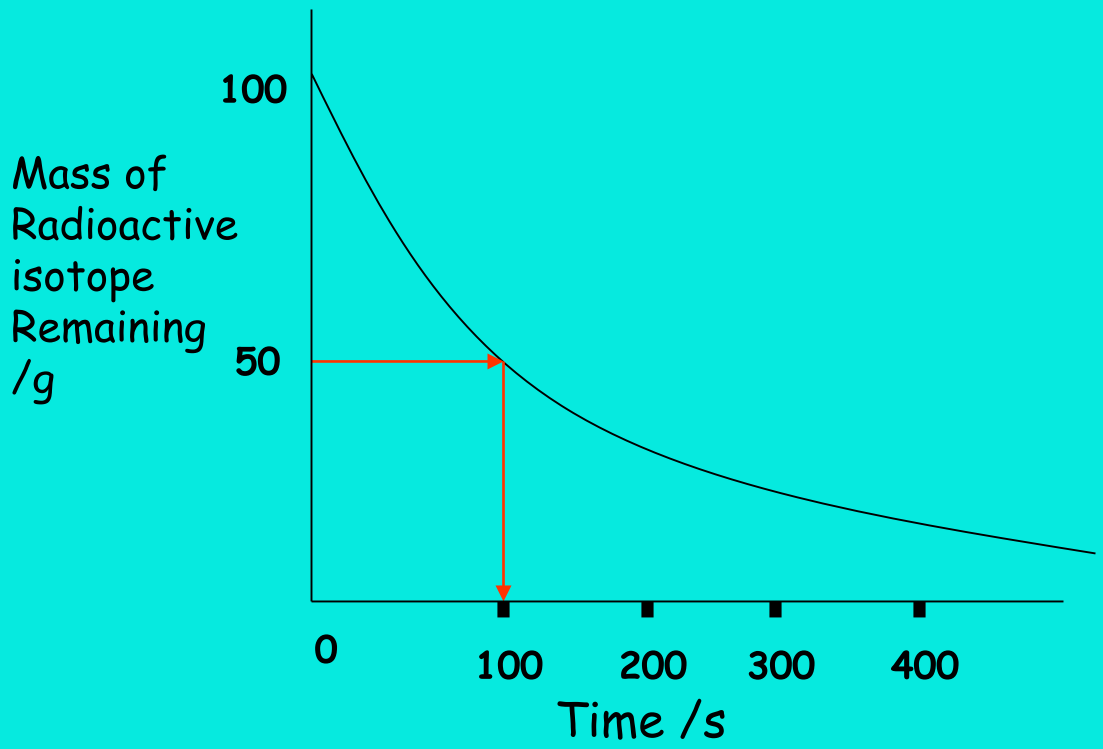
The half life of ^{14}C is 5,730 years.

$$^{14}_{6}C \ 100g \xrightarrow{t_{1/2}} \ ^{14}_{6}C \ 50g \xrightarrow{t_{1/2}} \ ^{14}_{6}C \ 25g \xrightarrow{t_{1/2}} \ ^{14}_{6}C \ 12.5g$$

100g of ^{14}C would decay to 12.5g in 3 x $t_{1/2}$,

i.e. 5,730 x 3 years = 17,190 yrs

Radioactive half life



Isotope	Half-life
Polonium-214	0.164 second
Oxygen-15	2 minutes
Bismuth-212	60.5 minutes
Sodium-24	15 hours
Iodine-131	8 days
Phosphorus-32	14.3 days
Cobalt-60	5.3 years
Carbon-14	5,730 years
Plutonium-239	24,110 years
Uranium-238	4.5 billion years

The time it takes this radioactive isotope to reduce its mass by a half is 100 s.
i.e. The mass of the radioactive isotope has changed form 100 g to 50 g.

The half life is therefore 100 s.

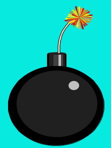
Radioactive Isotopes

Medical:
^{99}Tc (Technetium) is used in tracers to detect brain tumours.
^{24}Na allows doctors to follow the movement of Na ions in the kidneys.
^{15}O is used in PET (Positron emission tomography) to monitor blood flow.
Radiotherapy uses gamma emitters such as ^{60}Co to kill cancer cells.
The most frequently used radioisotopes for radioactive labelling in medical and pharmaceutical domains are carbon-14, fluorine-18, hydrogen-3 (tritium), iodine-131, sodium -24 and strontium-89. These radioisotopes are indirect γ emitters

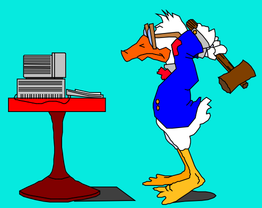
Industrial:
^{241}Am is an alpha emitter used in smoke detectors.
Gamma sources are used to sterilise foods and medical kits.
Gamma sources are used to detect leaks in pipes.
Beta sources can be used in automatic filling machines.

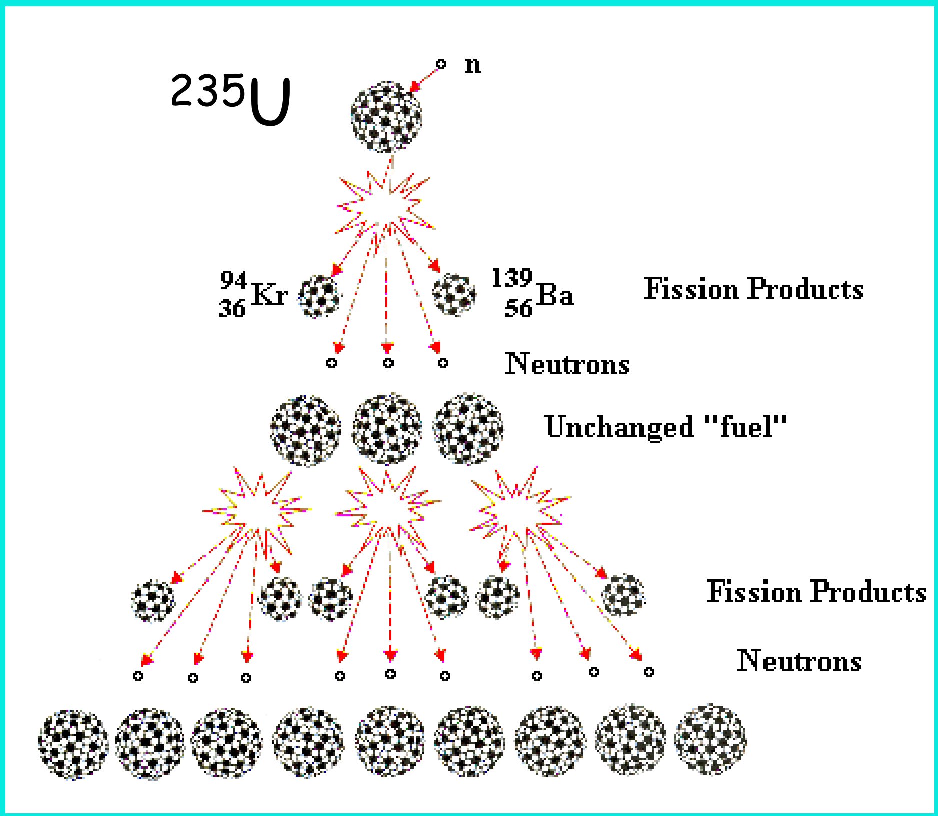
Chemical research

The radioactive isotopes can be used to trace the path of an element as it passes through various steps from reactant to product. C-14 can be used as a radioactive label. e.g. in photosynthesis.



Nuclear Energy Fission





In nuclear fission the nuclei of heavier elements break up into two smaller lighter nuclei and release a large output of energy.

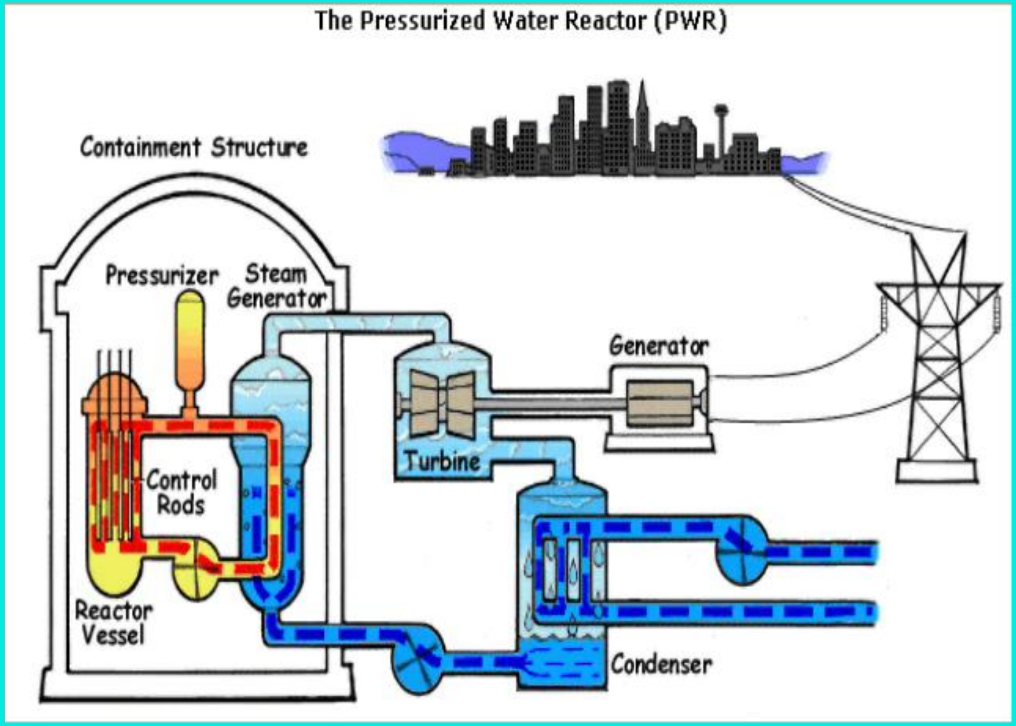
^{239}Pu and ^{235}U are the only important fissionable isotopes. 0.7% of natural uranium contains ^{235}U.

enrichment of uranium ore produces 2-3% ^{235}U, sufficient for fission.

$$^{235}_{92}U \longrightarrow \, ^{139}_{56}Ba + \, ^{94}_{36}Kr + 3\,^{1}_{0}n$$

Energy 10^{10} kJ per mol

Nuclear Energy



Nuclear Reactors

AGR uses CO_2 gas to transfer heat from the reactor. Other reactors use either water (PWR) or liquid Na.

Some reactors use natural U fuel, with 0.7% ^{235}U, Others need enriched U fuel, containing 3 % ^{235}U

1. **Fuel rods**, steel tubes containing either ^{235}U or ^{235}U oxide. The fission process generates heat in these rods.
2. **Moderators**, graphite blocks which slow down neutrons enabling them to be more easily captured by the uranium.
3. **Control rods**, contain boron, which absorbs neutrons. Lowering and raising these rods controls the fission process.

Reprocessing spent Nuclear Fuel

Reprocessing

After several years the fuel becomes less efficient and is replaced. This spent fuel is a mixture of unused uranium, plutonium and waste fission products.

1. Plutonium is produced when ^{238}U is combined with slow neutrons.

$$^{1}_{0}n + ^{238}_{92}U \longrightarrow ^{239}_{93}Pu + ^{0}_{-1}e$$

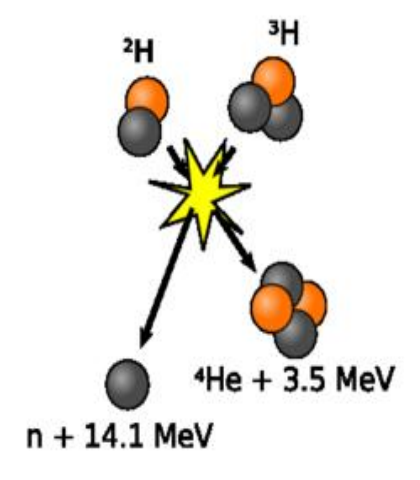
Plutonium does not occur naturally but is capable of fission and is therefore used as an alternative fuel. Fast travelling neutrons are needed, so a moderator is not needed.

2. Spent fuel contains both short and long lived radioactive isotopes. The rods are stored under water to allow them to cool and the short lived isotopes to decay. The spent fuel is sent to Sellafield (reprocessing plant) where the other isotopes are recovered.

3. Storing As yet, nobody has come up with a safe way of storing this long lived radioactive waste. Ideas include, burial deep underground and encasing in glass,

Nuclear Energy, Fusion

Nuclear fusion is the reverse of nuclear fusion. Two light nuclei are fused together to produce a heavier nucleus.



Hydrogen-2(deuterium) and hydrogen-3(tritium), release 1.7×10^9 kJ when one mole of one fuses with the other.

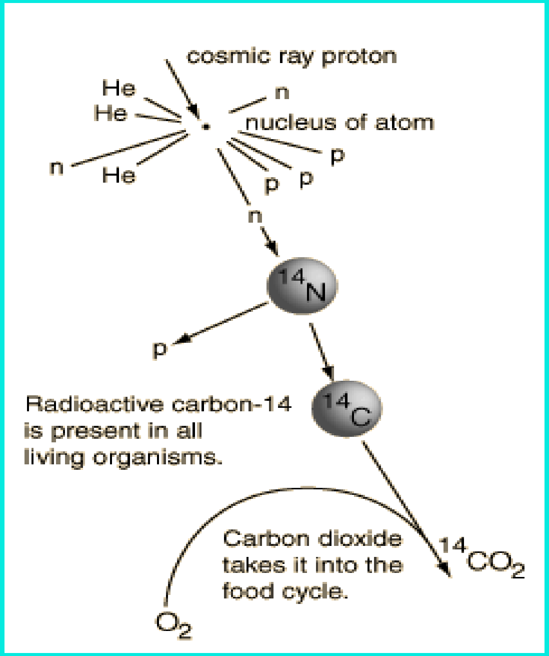
$$^{2}_{1}H + ^{3}_{1}H \longrightarrow ^{4}_{2}He + ^{1}_{0}n$$

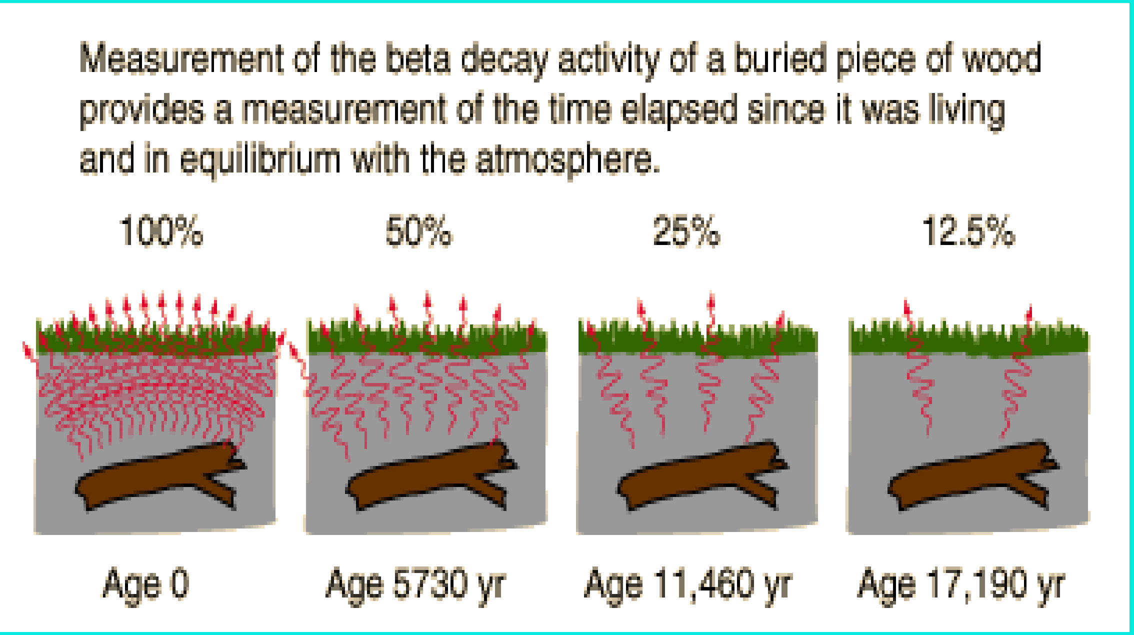
This reaction takes place in the centre of stars, which have sufficiently high temperatures and pressures to allow this reaction to take place.

This reaction can eventually produce the heavier elements such as oxygen, carbon and iron.

The hope for commercial fusion plants is some way off, but a prototype reactor is being built in France.

Radioisotopes and carbon dating





http://hyperphysics.phy-astr.gsu.edu/hbase/nuclear/cardat.html

Neutrons from cosmic radiation collide with nitrogen and create a proton and carbon-14 atoms.

$$^{1}_{0}n + ^{14}_{7}N \longrightarrow ^{14}_{6}C + ^{1}_{1}H$$

The half-life of ^{14}C is 5730 years.

Radioisotopes and dating rocks

One of the important natural radioactive isotopes is ^{40}K. It has a life of 1.3 x 10^9 years. 0.012% of all K is made from this isotope.
The constant rate of change between ^{40}K and ^{40}Ar allows for the K/Ar ratio to be used to determine the age of rocks.

Rocks can also be dated using ^{238}U, which has a half life of 4.5x10^9 years. ^{238}U decays to ^{234}Th and then eventually to ^{206}Pb.
The ratio of ^{238}U to ^{206}Pb can be used to dates the rock.

Dating materials less than 100 years old uses tritium, (formed by cosmic radiation) a beta emitter with a half life of 12 years. calculating the ratio of ^{1}H to ^{3}H is a measure of the age of under ground water.