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Physics notes-Nuclear physics & radioactivity

Structure and Properties of the Nucleus

In the early 1930s a model of the nucleus was developed that is still useful today. According to this model, a nucleus is considered as an aggregate of two types of particles: **protons** and **neutrons**. In the simplest atom (hydrogen atom), the nucleus is a proton.

A proton is an elementary particle which has a positive charge of $+e = +1.60\times10^{-19}$ C and a mass of $m_p = 1.6726\times10^{-27}$ kg.

A neutron is a neutral particle which has a mass almost identical to that of a proton, $m_n = 1.6749\times10^{-27}$ kg.

These two particles are referred to collectively as **nucleons**.

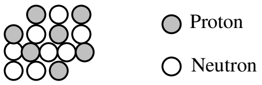
The different types of nuclei are referred to as **nuclides**.

The number of protons in a nucleus (or nuclide) is called the **atomic number** and is designated by the symbol Z.

The total number of nucleons, neutrons and protons, is called the **mass number** and is designated by the symbol A.

The **neutron number** N is $N = A - Z$.

To specify a nuclide, we use the special symbol ${}^{A}_{Z}X$, e.g. a normal nitrogen nuclide ${}^{15}_{7}N$ means that a nitrogen nucleus contains 7 protons and 15 nucleons and $\therefore$ it has 8 neutrons.



Nuclei of atoms of the same element that contain the same number of protons but different numbers of neutrons are called **isotopes**.
For example, ${}^{11}_{6}C$, ${}^{12}_{6}C$, ${}^{13}_{6}C$, ${}^{14}_{6}C$, ${}^{15}_{6}C$ and ${}^{16}_{6}C$ are all isotopes of carbon. 98.9% of naturally occurring carbon is the isotope ${}^{12}_{6}C$ and about 1.1% is ${}^{13}_{6}C$.

What hold the nucleons together to form a nucleus?

Protons are positively charged particles and thus exert electric repulsive force on each other. Since stable nuclei do stay together, there must be a second force acting within each nucleus and it must be stronger than the electric force. It is called the **strong nuclear force**. It is an attractive force that acts among all nucleons.

The strong nuclear force is a comparatively **short-range** force, i.e. it acts only over a very short distance. It is very strong between two nucleons if they are less than about 10^{-15} m apart, but it is essentially zero if they are separated by a distance greater than this.

Electric and **gravitational** forces can act over long distances and they are called **long-range** forces.

Stable and unstable nuclei

A **stable** nucleus is one that stays together indefinitely.

For small atoms (up to $A \approx 30 \rightarrow 40$) their nuclei tend to have the same number of protons as neutrons and they are stable nuclides.

For larger atoms, stable nuclides contain more neutrons than protons. As the number of protons increases, the electrical repulsion increases, so more neutrons (which exert only the attractive nuclear force) are required to maintain **stability**.

For very large atom, no number of neutrons can overcome the greatly increased electric repulsion. There are no known stable nuclides above $Z = 82$.

If a nuclide contains too many or too few neutrons relative to the number of protons, the nuclear force is weakened and the nuclide is **unstable**.

Radioactive decays

An unstable nucleus is one that comes apart. This is known as **radioactive decay** or **disintegration**. This phenomenon is called **radioactivity**.

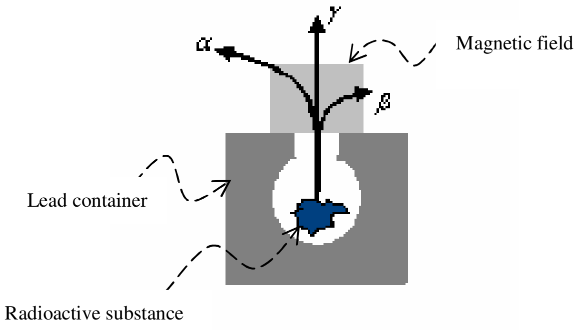
Many unstable isotopes occur in nature, and their radioactivity is thus called **natural radioactivity**. Other unstable isotopes can be produced artificially in the laboratory by nuclear reactions and their radioactivity is called **artificial radioactivity**.

The unstable isotopes are called **radioisotopes**.

During decays of unstable nuclei, some type of **radiation** or **rays** is emitted.

The radiation can be classified into three distinct types. They are named as **alpha** α, **beta** β and **gamma** γ.

Alpha and beta rays consists of charged particles and are bent in opposite directions by a magnetic field, whereas gamma radiation consists of neutral particles and is not affected by a magnetic field and does not bend at all.



Alpha decay

In an alpha decay an alpha particle is emitted. An alpha particle is simply the nucleus of a helium atom. It has two protons and two neutrons bound together.

$$\alpha\text{-particle} = {}_{2}^{4}He$$

When a nucleus emits an α-particle, it loses two protons and two neutrons resulting in a different nucleus, i.e. a new element is formed. This change is called **transmutation**.

Example 1 Radium 226 (${}_{88}^{226}Ra$) undergoes alpha decay. We say it is an α-emitter. It decays to become another element, radon. This decay is written as

$${}_{88}^{226}Ra \rightarrow {}_{86}^{222}Rn + {}_{2}^{4}He \text{ or } {}_{88}^{226}Ra \rightarrow {}_{86}^{222}Rn + \alpha$$

In decays, the original nucleus is called the **parent nucleus** and the new one is the **daughter nucleus**.

Example 2 ${}_{92}^{232}U \rightarrow {}_{90}^{228}Th + {}_{2}^{4}He$

Example 3 ${}_{84}^{210}Po \rightarrow {}_{82}^{206}Pb + {}_{2}^{4}He$

In a decay (or nuclear reaction), the total mass of the products is less than the total mass of the parent nucleus (or nuclei). The 'missing mass' is transformed to energy according to Einstein's famous equation,

$$E = mc^2 .$$

Mass is a form of energy. A small difference in mass will give rise to a large amount of energy. This energy appears as the kinetic energy which is carried away mainly by the emitted particle in a decay.

Why do nuclei emit an α-particle rather than four individual nucleons or just one?

The 2 protons and 2 neutrons in α-particle are very strongly bound and thus a large amount of energy is required to separate them.

Beta (negative) decay

Transmutation of elements also occurs when a nucleus decays by emitting a negative beta particle β^-. It is in fact an electron ${}_{-1}^{0}e$. The electron emitted is not one of the orbital electrons in an atom. It is created within the nucleus itself according to the theory that a neutron in the nucleus changes to a proton and an electron is emitted.

$$n \rightarrow p + {}_{-1}^{0}e \text{ or } n \rightarrow p + \beta^-$$

Example 1 Carbon-14 emits a β^--particle when it decays. The nucleus gains a proton and becomes nitrogen-14.

$${}_{6}^{14}C \rightarrow {}_{7}^{14}N + {}_{-1}^{0}e \text{ or } {}_{6}^{14}C \rightarrow {}_{7}^{14}N + \beta^-$$

In fact there is another particle emitted during the β^- decay. It is called neutrino, or anti-neutrino to be exact, and has the symbol $\bar{\nu}$. The correct way to write the decay of carbon-14 is then

$${}_{6}^{14}C \rightarrow {}_{7}^{14}N + {}_{-1}^{0}e + \bar{\nu} .$$

Beta (positive) decay

Many isotopes decay by electron (beta) emission. They are isotopes that have too many neutrons compared to the number of protons.

Isotopes that have too few neutrons compared to the number of protons decay by emitting a **positron** instead of an electron.

A positron (symbols: $e^+, \beta^+, {}_{+1}^{0}e$) has the same mass as the electron but it is opposite in charge to the electron. It is called an **anti-particle** of the electron. Positron is also created within the nucleus according to the theory that a proton in the nucleus changes to a neutron and a positron is emitted.

$$p \rightarrow n + {}_{+1}^{0}e \text{ or } p \rightarrow n + \beta^+$$

Example 1 ${}_{10}^{19}Ne \rightarrow {}_{9}^{19}F + {}_{+1}^{0}e + \nu$

An anti-electron (i.e. positron) is emitted with a neutrino ν, and an electron is emitted with an anti-neutrino $\bar{\nu}$.

Gamma decay

Gamma rays are electromagnetic radiation in the same category as radio waves, visible light and X-ray etc, except it has much higher energy. Since gamma ray carries no charge, the same element remains as a result of gamma decay.

The daughter nucleus may be left in an excited state after the radioactive decay of its parent. It then returns to the non-excited state (called the **ground state**) by gamma decay.

Example 1 ${}_{5}^{12}B \rightarrow {}_{6}^{12}C^* + {}_{-1}^{0}e$, then ${}_{6}^{12}C^* \rightarrow {}_{6}^{12}C + \gamma$.

Half-life of a radio-isotope

A sample of any radioactive isotope consists of a huge number of radioactive nuclei. They do not all decay at the same time. Rather, they decay one by one over a period of time and it is a random process. We cannot predict exactly when a particular nucleus will decay, but we can determine approximately how many nuclei in the sample will decay over a given period of time.

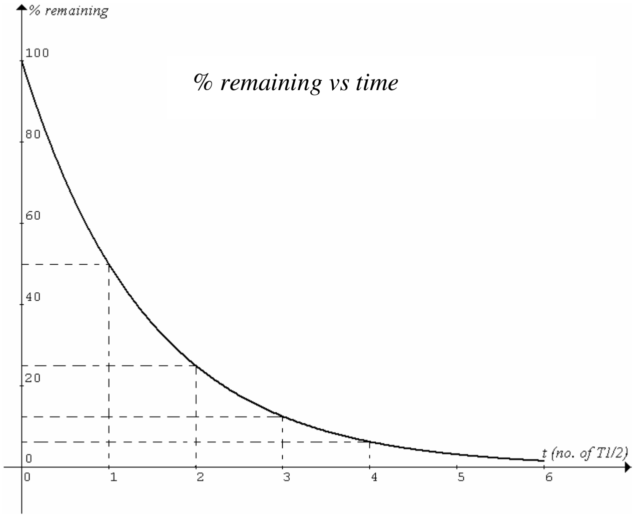
The **rate of decay** is called the **activity** A of a given sample. It is proportional to the size of the sample remaining. It is measured in number of decays per second.

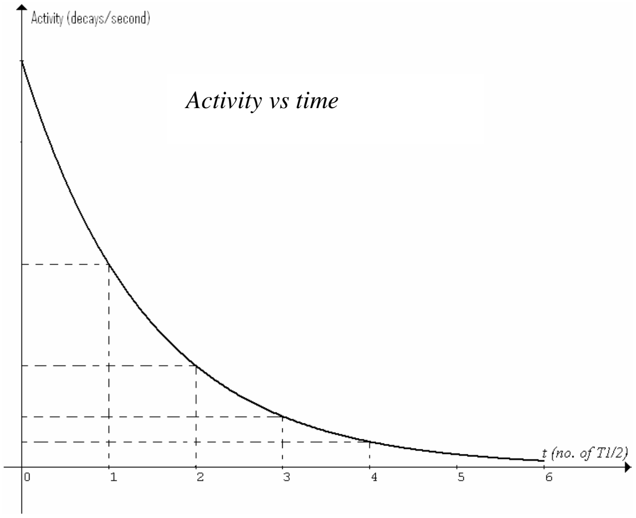
$$A = \frac{N}{\Delta t}$$

The **half-life** $T_{\frac{1}{2}}$ of an isotope is defined as the time it takes for half of the remaining sample to decay.

Radio-isotope	Half-life
Uranium-238	4.5×10^9 years
Carbon-14	5730 years
Cobalt-60	5.3 years
Iodine-131	8 days
Polonium-214	164 μs

Half-life graphs





Example 1 Find the % of a sample of Iodine-131 decayed after 32 days. Find the % of the original activity of the sample remaining.

The half-life of Iodine-131 is 8 days. 32 days (4 half-lives) later, only 6.25% remaining. $\therefore$93.75% decayed.

Since activity is proportional to the size of the sample remaining, only 6.25% of the original activity remaining.

Example 2 When the solar system acquired its present form about 5×10^9 years ago, it is believed that nearly all nuclides had been formed. Many radio-isotopes with short half-lives decayed quickly and no longer exist in nature today. Long-lived isotopes, such as ${}^{238}_{92}U$ with a half-life of 4.5×10^9 years, are found in abundance in Australia and elsewhere on earth. Estimate the % of the original ${}^{238}_{92}U$ still remaining on earth.

$\frac{5}{4.5} \approx 1.1$ half-lives. From the half-life graph, about 47%.

Example 3 A radioactive material registers 1573 counts in a minute on a Geiger counter at one time, and 8 hours later registers 1180 counts in three minutes. What is its half-life?

The activity of the material changes from 26.22 s^{-1} to 6.56 s^{-1} in 8 hours, i.e. in 8 hours the activity is 25% of the original activity. Since it takes 2 half-lives for the activity to drop to 25%, $\therefore T_{\frac{1}{2}} = 4$ hours.

Example 4 ${}^{124}_{55}Cs$ has a half-life of 30.8 s. How much of the original amount of 7.8 μg remains after 1.54 minutes?

1.54 min = 92.4 s $= 3\times30.8$ s = 3 half-lives.
After 3 half-lives, only 12.5% remaining,
i.e. 12.5% of 7.8 μg = 0.975 μg.

Example 5 Radium ${}^{226}_{88}Ra$ has a relatively short half-life in comparison with ${}^{238}_{92}U$, all the original ${}^{226}_{88}Ra$ nuclei must by now have decayed and vanished from the earth. Explain why ${}^{226}_{88}Ra$ still exists on earth today.

This is because the supply of ${}^{226}_{88}Ra$ is continually replenished due to the decay of ${}^{238}_{92}U$ in several steps to ${}^{226}_{88}Ra$. Refer to the decay series of ${}^{238}_{92}U$.

Example 6 The age of ancient materials can be determined by **radioactive dating**, e.g. Carbon-14 dating.

All living plants absorb carbon dioxide from the air. Most of these carbon atoms are carbon-12, only a tiny fraction is carbon-14.

When a plant or tree is alive, it continually absorbs carbon dioxide from the air and the ratio of carbon-14 to carbon-12 remains constant.

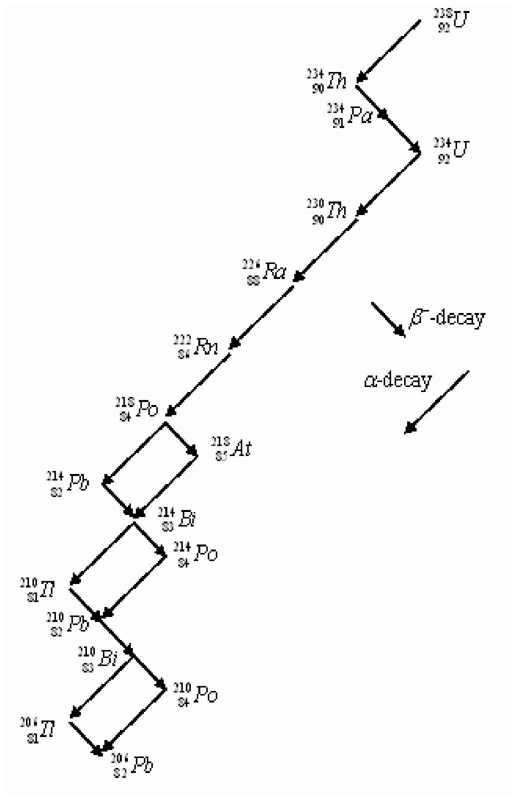
When the plant dies, the ratio decreases because carbon-14 undergoes radioactive decay and is not replenished.

Carbon-14 has a half-life of 5730 years. If the ratio of carbon-14 to carbon-12 for an ancient wooden object is half of what it is in living trees, then the object must have been made from a tree that was cut down about 5730 years ago.

Decay series

It is common occurrence that one radioactive isotope decays to another isotope which is also radioactive. This daughter decays to a third isotope that is also radioactive. Further decays occur until a stable isotope is reached. The successive decays form a **decay series**.

The following diagram shows the decay series of $^{238}_{92}U$.

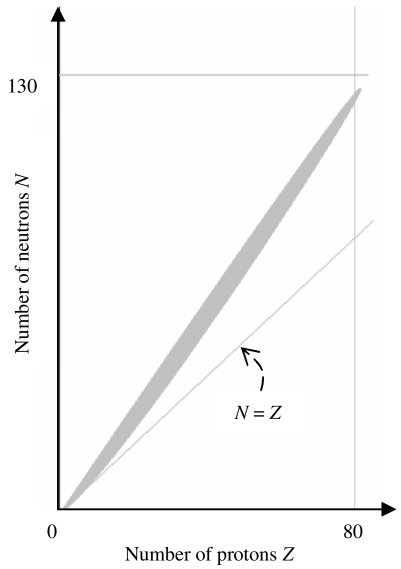


In a β^- decay the mass number of the isotope is unchanged and the atomic number increases by 1.

In an α decay the mass number of the isotope decreases by 4 and the atomic number decreases by 2.

Nuclear stability curve

An N vs Z plot of the position of all the stable nuclei forms a thin and slightly curved band called **stability line**. Unstable nuclei below the band tend to undergo α or β^+ decay whilst those above the band undergo β^- decay to nuclei within it.



Passage of radiation through matter

Charged particles, such as alpha and beta particles and protons, can **ionise** the material they pass through because of the electric force. They can attract or repel electrons to remove them from the atoms of the material. A single alpha or beta particle can cause thousands of **ionisations**.

Exposure to neutral radiations such as X-ray and γ-ray may also give rise to ionisation. Electrons of atoms can be knocked out as in the photoelectric and Compton effects.

Neutrons interact with matter mainly by collisions with nuclei. Often a nucleus in a molecule is broken apart by such a collision and thus the structure of the molecule changes.

Radiation damage

Radiation passing through matter can do considerable damage.

Metals and other structural materials become brittle and their strength can be weakened if the radiation is very intense.

The radiation damage produced in biological organisms is caused by ionisation in cells. Ions (radicals) are produced which are highly reactive and take part in chemical reactions that interrupt the normal operation of the cell.

Risks of external and internal sources to the human body

Type	External source	Internal source
Alpha (α)	Low	High
Beta (β)	Medium	Medium
Gamma (γ)	High	Low

Possible effects from low radiation dose (well below 1 Sv)

Relatively low doses of radiation can cause: cancer and subsequent death; gene damage and will pass on genetic defects to offspring. No level of radiation exposure is safe.

Possible effects from high radiation dose (1 Sv or above)

Initial symptoms within hours/days: impaired vision, nausea, vomiting and diarrhoea, internal bleeding, convulsion and eventual death.

Penetrating properties of radiations

Type	Penetrating property
Alpha (α)	Can penetrate a few cm of air, easily stopped by a sheet of paper or bare skin
Beta (β)	Can penetrate a few m into the air, about 2 cm into human flesh
Gamma (γ)	Extremely penetrating, requires thick lead or concrete shielding to stop it
Neutron (n)	More penetrating than gamma radiation

Detection of radiation

Type	Detector
Alpha (α)	Geiger counter with very thin window
Beta (β)	Geiger counter (filled with argon gas)
Gamma (γ)	Scintillation detector
Neutron (n)	Geiger counter (filled with BF_3 gas)
Personal radiation levels	Thermoluminescent dosimeter TLD

Measurement of radiation

The strength of a radioactive source can be specified at a given time by stating the **source activity**, i.e. how many disintegrations (decays) occur per second.

The SI unit for source activity is the becquerel (Bq).

$$1\ \text{Bq} = 1\text{decay per second}$$

Another type of measurement is the exposure or **absorbed dose**, i.e. the amount of energy (J) absorbed by each kilogram of the absorbing material.

The SI unit for absorbed dose is the gray (Gy).

$$1\ \text{Gy} = 1\ \text{J kg}^{-1}$$

Equal doses of different types of radiation will cause differing amounts of damage. $\therefore$ Gy is not the most meaningful unit to measure the biological damage produced by radiation.

For example, for the same dose (say 1Gy), X and γ-rays, β-ray and fast protons do about the same amount of damage. Slow neutrons cause about 3 times as much, fast neutrons up to 10 times and α-particles up to 20 times.

The relative ability in causing biological damage for the different types of radiation is given by a number called the **quality factor** (QF).

Type	QF
X and γ-rays	Approx. 1
β-ray	Approx. 1
Fast protons	Approx. 1
Slow neutrons	Approx. 3
Fast neutrons	Up to 10
α-particles	Up to 20

A third type of measurement is the **dose equivalent**. It measures the amount of biological damage done to a kilogram of tissues.

$$\text{Dose equivalent} = \text{Absorbed dose} \times \text{QF}$$

The SI unit for effective dose is the sievert (Sv).

$$1\ \text{Sv} = 1\ \text{Gy} \times \text{QF}$$

Example 1 Calculate the dose equivalent for each of the following radiations.

(a) 10 Gy of β-ray (QF = 1)
(b) 0.5 Gy of α-ray (QF = 20)
(c) 1 Gy of fast neutrons (QF = 10)

(a) $10 \times 1 = 10$ Sv (b) $0.5 \times 20 = 10$ Sv (c) $1 \times 10 = 10$ Sv

Example 2 What is the absorbed dose of α-ray (QF = 15) which will cause the same amount of biological damage to body tissues as 10 Gy of slow neutrons (QF = 3)?

Let x Gy be the absorbed dose of α-ray (QF = 15).
$x \times 15 = 10 \times 3$, $\therefore x = 2$.

When the human body is exposed to nuclear radiation, the effects on the internal organs of the body are different. Instead of using dose equivalent to generalise the risk of radiation damage, dose equivalent is multiplied by another factor called the risk factor RF. This new measurement is called the **effective dose** of the radiation. It is also measured in Sv but it is organ specific.

Organ	RF
Lungs	0.12
Red bone marrow	0.12
Thyroid	0.13
Breast	0.15
Ovaries/testes	0.25
Other parts	0.30

Example 1 A person received an absorbed dose of 1.0 Gy when irradiated by γ-rays. What would be the effective dose to the person's lungs?

$$\text{Effective dose} = \text{absorbed dose} \times \text{QF} \times \text{RF}$$
$$= 0.8 \times 1 \times 0.12 \approx 0.1 \ \text{Sv}$$

Natural and artificial radio-isotopes

Over 60 radionuclides can be found in nature, and they can be classified in three general categories:

1. **Primordial** - formed since the creation of the Earth

Nuclides	Half-life	Source and activity
^{238}U	4.47 x 10^{9} yr	99.275% of all natural uranium
^{235}U	7.04 x 10^{8} yr	0.72% of all natural uranium
^{232}Th	1.41 x 10^{10} yr	Av.10 ppm in the common rock types
^{226}Ra	1.60 x 10^{3} yr	16 Bq/kg in limestone; 48 Bq/kg in igneous rock
^{222}Rn	3.82 days	Noble Gas; average air concentrations range between 1 and 30 Bq/m^{3}
^{40}K	1.28 x 10^{9} yr	Between 0.05 and 1 Bq/g of soil

2. **Cosmogenic** - formed as a result of cosmic ray interactions

Nuclides	Half-life	Source and activity
^{14}C	5730 yr	Cosmic-ray interactions, 0.22 Bq/g
^{7}Be	53.28 days	Cosmic-ray interactions with N and O, 0.01 Bq/kg
^{3}T	12.3 yr	Cosmic-ray interactions with N and O, 1.2 x 10^{-3} Bq/kg

3. **Artificial** - formed by human

Nuclides	Half-life	Source
^{239}Pu	2.41 x 10^{4} yr	Produced by neutron bombardment of ^{238}U
^{137}Cs	30.17 yr	Fission product from weapons testing and fission reactors
^{131}I	8.04 days	Fission product from weapons testing and fission reactors, used in medical treatment of thyroid problems
^{129}I	1.57 x 10^{7} yr	Fission product from weapons testing and fission reactors
^{99m}Tc	6.03 hr	Decay product of ^{99}Mo, used in medical diagnosis
^{99}Tc	2.11 x 10^{5} yr	Decay product of ^{99m}Tc
^{90}Sr	28.78 yr	Fission product from weapons testing and fission reactors
^{3}H	12.3 yr	From weapons testing and fission reactors; reprocessing facilities, nuclear weapons manufacturing

http://www.umich.edu/~radinfo/introduction/natural.htm

Nuclear reactions

A nuclear reaction is said to occur when a nucleus is struck by another nucleus, or by a simpler particle such as a neutron, or even by a gamma ray, so that an interaction takes place.

Example 1 When α-particles pass through nitrogen gas, some are absorbed and protons are emitted.

$$_{2}^{4}He + _{7}^{14}N \rightarrow _{8}^{17}O + _{1}^{1}H$$

Example 2 In the atmosphere the radio-isotope carbon-14 is continually being made through the following naturally occurring nuclear reaction, where neutrons in the cosmic radiation collide with the nitrogen nuclei.

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

Nuclear fissions

When uranium-235 is bombarded by neutrons, two smaller nuclei about half the size of the original uranium nucleus are produced. This process is called **nuclear fission**. The resulting nuclei are called **fission fragments**, and in the process two or three neutrons are given off.

A typical fission reaction is:

$$n + _{92}^{235}U \rightarrow _{56}^{141}Ba + _{36}^{92}Kr + 3n$$

Other observed fission reactions are:

$$n + _{92}^{235}U \rightarrow _{54}^{143}Xe + _{38}^{90}Sr + 3n$$

$$n + _{92}^{235}U \rightarrow _{54}^{136}Xe + _{38}^{88}Sr + 12n$$

The above fission reactions are possible only for *slow* neutrons.