Experimental work around the turn of the 20th Century by Henri Becquerel (1852 - 1908), Ernest Rutherford (1871 - 1937), Marie Curie (1867 – 1934) and Pierre Curie (1859 – 1906 ) and others indicated that three kinds of natural radiations: alpha particles $\alpha$, beta particles $\beta$ and gamma rays $\gamma$ were emitted from a nucleus of an unstable atom.

These radiations were emitted naturally from certain elements such as uranium, polonium, radium, and actinium. Further, it was found that the emission of natural radiations by one element usually led to the production of a different element. For instance, radium was produced as a result of the radioactive decay of uranium. This change of a parent nucleus into a different daughter nucleus is called a nuclear transmutation. One element effectively changes into another element.

When transmutation occurs, the sum of the atomic numbers on the left hand side of the nuclear equation equals the sum of the atomic numbers on the right hand side. Likewise, the sum of the mass numbers on the left hand side of the nuclear equation equals the sum of the mass numbers on the right hand side.

\[
\begin{align*}
\text{Alpha decay} & \quad 232^{\text{Th}} \rightarrow 228^{\text{Ra}} + ^4_2\text{He} \quad ^4_2\text{He} \equiv \alpha \\
\text{Beta decay} & \quad 13^{\text{N}} \rightarrow 13^{\text{C}} + ^{\beta^+}_0 + ^{\nu}_e \quad ^{\beta^+}_e \equiv ^0_e \equiv e_1
\end{align*}
\]
**ALPHA DECAY**

An alpha particle (\(\alpha\) particle) is a helium nucleus \(^4\text{He}_2\) that is naturally emitted from an unstable nucleus producing a nucleus of a new element.

Emission of a \(^4\text{He}_2\) nucleus: \(N \rightarrow (N - 2)\) \(Z \rightarrow (Z - 2)\) \(A \rightarrow (A - 4)\)

Transmutation of a parent P into its daughter D:

\[ ^A_P \rightarrow ^{A-4}_D + ^4\text{He}_2 \]

**Example**

\[ ^{226}_{88}\text{Ra} \rightarrow ^{222}_{86}\text{Rn} + ^4\text{He}_2 \]

Alpha decay occurs because the strong nuclear force is unable to hold large nuclei together \((Z > 82)\). The attractive strong nuclear force only acts between neighbouring nucleons since it is short ranged. However, the repulsive electrostatic force is long ranged and acts all the way across a nucleus and dominates the strong nuclear force. An \(\alpha\) particle is very a very tightly bound unit and this is why a helium nucleus is emitted rather than some other combination of protons and neutrons.

A gamma ray is emitted when a parent nucleus decays by emitting an alpha particle and the daughter nucleus is left in an excited state \((^*\)\). The excited daughter nucleus than emits a gamma ray. So in an \(\alpha\) source, \(\gamma\) rays are often emitted as well as the \(\alpha\) particles.

\[ ^{226}_{88}\text{Ra} \rightarrow ^{222}_{86}\text{Rn} + ^4\text{He}_2 \quad \text{energy of } \alpha \text{ particle} \quad 4.871 \text{ MeV} \]

\[ ^{226}_{88}\text{Ra} \rightarrow ^{222}_{86}\text{Rn}^* + ^4\text{He}_2 \quad \text{energy of } \alpha \text{ particle} \quad 4.685 \text{ MeV} \]

\[ ^{222}_{86}\text{Rn}^* \rightarrow ^{222}_{86}\text{Rn} + \gamma \quad \text{energy of } \gamma \text{ ray} \quad 0.186 \text{ MeV} \]

The excited nucleus can also be represented by the superscript \(m\), e.g., \(^{222m}_{86}\text{Rn}\)

One widespread application of nuclear physics is present in nearly every home in the form of an ordinary smoke detector.

**Web search:** How does a smoke detector work?

Alpha particles have the least penetrating power compared to beta particles and gamma rays as they move with a smaller velocity. Alpha particles very easily ionize the atoms in there vicinity and hence loss energy very rapidly and therefore do not travel very far into a material. In air, alpha particles only travel about 100 mm.

Alpha particle are not particularly dangerous to a person with external exposure. However, if ingested, they can cause serve damage to cells and organs because of the high ionizing power.
BETA DECAY

Suppose now that a nucleus exists which has either too many or too few neutrons relative to the number of protons present for stability. Stability can be achieved by the conversion inside the nucleus of a proton into a neutron or a neutron into a proton. In this transmutation:

\[ \text{Charge is conserved } \Rightarrow \text{ a beta particle (}\beta^+ \text{ or } \beta^-\text{) is emitted from the nucleus} \]

\[ \text{Energy and momentum are conserved } \Rightarrow \text{ a particle called a neutrino (}\nu_e \text{ or } \bar{\nu_e}\text{) must also be emitted from the nucleus.} \]

Greek letter \( nu \) (\( \nu \))

Reduction of a neutrons & increase in a proton inside nucleus \( N / Z \) too large

\[ n \rightarrow p^+ + e^- + \bar{\nu_e} \quad e^- \equiv \beta^- \]

\[ N \rightarrow N - 1 \quad Z \rightarrow Z + 1 \quad A \rightarrow A \]

\[ ^{A}P_{Z} \rightarrow ^{A}D_{Z+1} + e^- + \bar{\nu_e} \]

\[ ^{14}C_{6} \rightarrow ^{14}N_{7} + e^- + \bar{\nu_e} \]

The electron \( e^- \) emitted in \( \beta \) decay is not an orbital electron, the electron is created in the nucleus itself. We use the term \( \beta \) particle for the electron to show its origin, nonetheless it is indistinguishable from an orbital electron. The symbol \( \bar{\nu_e} \) represents the particle called the electron antineutrino (antiparticle of the electron neutrino).

A free neutron can also decay but not a free proton (on average a free neutron at rest lives for \(~15\) minutes)

\[ n \rightarrow p^+ + e^- + \bar{\nu_e} \]

Reduction of a proton & increase in a neutron inside nucleus \( N / Z \) too small

\[ p^+ \rightarrow n + e^+ + \nu_e \quad e^+ \equiv \beta^+ \]

\[ N \rightarrow N + 1 \quad Z \rightarrow Z - 1 \quad A \rightarrow A \]

\[ ^{A}P_{Z} \rightarrow ^{A}D_{Z-1} + e^+ + \nu_e \]

\[ ^{19}Ne_{10} \rightarrow ^{19}F_{9} + e^+ + \nu_e \]

To conserve charge, the beta particle emitted is the positron \( e^+ \). The positron is identical to an electron except that its charge is positive and is the antiparticle of the electron. In this transmutation an electron neutrino \( \nu_e \) is also emitted.
**Electron capture**

Besides $\beta^-$ and $\beta^+$ emissions, there is a third process called *electron capture* and occurs when a nucleus captures (absorbs) one of its orbiting electrons

\[
N \rightarrow N + 1 \quad Z \rightarrow Z - 1 \quad A \rightarrow A \\
^{A}_{Z}P_{Z} + e^{-} \rightarrow ^{A}_{Z-1}D_{Z-1} + \nu_{e} \\
^7_{4}Be_{4} + e^{-} \rightarrow ^7_{3}Li_{3} + \nu_{e}
\]

Beta rays are more penetrating than alpha rays and move at a very high speed.

**THE NEUTRINO**

In beta decay a more stable nucleus is produced and hence in the process energy is liberated as kinetic energy of the products. It was first envisaged that the products of beta decay were the only the daughter nucleus and an electron. Since daughter nucleus has a mass much larger than that of an electron it would recoil only very slowly with small energy whereas the electron would gain most of the energy liberated. Hence, it was expected that the emitted electrons in beta decay would have a fixed kinetic energy in a given beta decay transmutation.

But it was found experimentally that the kinetic energy of the emitted electron could have any value from zero up to the maximum value. It was if the law of conservation of energy was violated. Careful measurements indicated that linear and angular momentum were also not conserved.

Figure (1) shows the energy spectrum for the decay of bismuth into polonium.

![Energy Spectrum of Beta Decay](image)

**Fig. 1.** Beta decay of bismuth-210 into polonium-210 where a neutron changes into a proton.
The need to account for the energy distribution of electrons emitted in beta decay (figure 1) and to satisfy the laws of conservation of energy, linear and angular momentum, Austrian physicist Wolfgang Pauli in 1930 proposed that a neutral particle was emitted along with the β particle. This particle would have no charge and zero rest mass (hence, travel at the speed of light) but would possess spin, energy and momentum. For each beta emission, the total energy carried away from the decaying nucleus would be shared between the beta particle and the neutral particle emitted with it - it would be expected that the beta particles emitted would have a range of energies depending on the energies of the neutral particles emitted with them.

In 1934, Italian physicist Enrico Fermi (1901 - 1954) named Pauli’s particle the neutrino (ν), meaning “little neutral one” in Italian, and formulated a theory of β decay using this particle. Fermi’s theory successfully explained all experimental observations. For instance, the shape of the energy curve shown in figure (1) for Bi-210 can be predicted from the Fermi Theory of beta decay.

Despite several ingenious attempts, the neutrino was not experimentally observed until 1956. In that year, two American Physicists, Cowan and Reines successfully identified the neutrino by detecting the products of a reaction that could only have been initiated by the neutrino.

It was Fermi who, in this theory postulated the existence of the fourth force in nature – the weak nuclear force. In beta decay, it is the weak nuclear force that plays the crucial role. β decay is often referred to as the weak interaction because it is $10^{12}$ times weaker than the strong nuclear force that holds the nucleus together. The neutrino is unique in that it interacts with matter only via the weak nuclear force, which is why it is so hard to detect.
**GAMMA DECAY**

**Gamma rays** ($\gamma$ rays) are **photons** having very high energy that were emitted from excited nuclei, much like emission of photons by excited atoms. Like an atom, a nucleus itself can be in an excited state. When it jumps down to a lower energy state it emits a photon called a $\gamma$ ray. The energy level separations in a nucleus (~ MeV) are much greater than the energy level differences in an atom (~ eV). For a given decay, the $\gamma$ ray always has the same energy and since the photon is electrically neutral, there is no change in the element as a result of the decay.

- Gamma rays are extremely high frequency (short wavelength) electromagnetic waves where the photons are emitted from excited nuclei.
- N, Z and A do not change

$$^{222}_{86}\text{Rn}^* \rightarrow ^{222}_{86}\text{Rn} + \gamma$$

A nucleus can be in an excited state after it suffers a violent collision with another particle, or more commonly the daughter nucleus remaining after an $\alpha$ decay or $\beta$ decay is left in an excited state.

$$^{226}_{88}\text{Ra} \rightarrow ^{222}_{86}\text{Rn}^* + ^4\text{He}_2 \quad \text{energy of } \alpha \text{ particle } 4.685 \text{ MeV}$$

$$^{222}_{86}\text{Rn}^* \rightarrow ^{222}_{86}\text{Rn} + \gamma \quad \text{energy of } \gamma \text{ ray } 0.186 \text{ MeV}$$

**What is the difference between a $\gamma$ ray and an X ray?**
Fundamentally there is no difference. They are both just high energy electromagnetic radiations, although $\gamma$ rays usually have higher energies. We distinguish between the two on how they are created:

The source of $\gamma$ rays is the nucleus.

The source of X rays electronic transition in an atom.

Gamma rays have very great penetrating power. They move at the speed of light and have a very short wavelength or high frequency. The energy of the photon of a gamma ray is $E = hf$

**Typical values** (check the calculations with your calculator):

$$\lambda \sim 3 \times 10^{-12} \text{ m} \quad f = c/\lambda \sim 10^{20} \text{ Hz} \quad E_{\text{photon}} \sim 7 \times 10^{-14} \text{ J} \sim 0.4 \text{ MeV}$$
PENETRATION POWER

Fig. 2. Relative penetrating powers of $\alpha$ particles, $\beta$ particles and $\gamma$ rays. The greater the density of the material, then the smaller the penetration through that material.

Alpha particles are the most ionizing form of radiation because the large charge and mass of the helium nucleus. Gamma rays are the least ionizing form of radiation because the photons have zero charge. Therefore, gamma rays are the most penetrating and alpha particles the least penetrating form of radiation.

(Ionization – removal of a bound electron from an atom to produce a free electron and a positive ion).

All radioactive emissions are extremely dangerous to living organisms. When alpha, beta or gamma radioactive emissions hit living cells they cause ionize atoms. They can kill cells directly or cause genetic damage to the DNA molecules. High radiation doses will cause burn effects as well as kill the damaged cells. However, low doses don't kill the cells, but if the cells are genetically damaged and can still replicate, these mutations can lead to the formation of cancerous cells and tumour development later.

When alpha, beta and gamma radiation collide with neutral atoms or molecules they knock off electrons and convert them into charged or ionised particles (ions). Positive ions are formed on electron loss and negative ions are formed by electron gain. The positive ions maybe unstable and very reactive and cause other chemical changes in the cell molecules. The three radiations have different capacities to cause cell damage.

If the radioactive source gets inside the body the danger order is

\[
\alpha > \beta > \gamma
\]

The bigger the mass or charge of the particle, the larger its ionising impact on atoms or molecule.

<table>
<thead>
<tr>
<th></th>
<th>alpha</th>
<th>beta</th>
<th>gamma</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ionizing power</td>
<td>10</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>mass</td>
<td>4</td>
<td>1/1850</td>
<td>0</td>
</tr>
<tr>
<td>charge</td>
<td>+2</td>
<td>+1</td>
<td>0</td>
</tr>
</tbody>
</table>

If the radioactive source is outside the body, the order danger is reversed:

\[
\gamma > \beta > \alpha
\]

because the danger order follows the pattern of penetrating power. The smaller the mass and charge the more penetrating the radiation.
Gamma and beta are the most penetrating and will reach vital organs in the body and be absorbed. Most gamma passes through soft tissue but some is inevitably absorbed by cells. Alpha radiation would not penetrate clothing and is highly unlikely to reach living cells.

Because of the dangers of this ionising or atomic radiation, all workers and medical staff who are likely to be near radioactive or ionising sources must wear lapel radiation badges containing photographic film to monitor their exposure to radiation. The film is regularly developed and the darker the film the more radiation would have impacted on the person.

Examples of precautions that can be taken include:

- Radiographers wear lead lined aprons and anyone else involved in radiotherapy cancer treatment must take particular precautions and radiation monitored.

- In nuclear fuel preparation and reprocessing, as much work is done using robotic control systems in behind steel, concrete, lead or thick lead glass panels for visual monitoring of the situation.

- In research laboratories, experiments are conducted in sealed fume cupboards at the laboratory side and technicians work through sealed whole arm gloves through a thick lead glass front. You can also reduce the pressure in the fume cupboard so there is no chance of pressure leakage out into the laboratory area.
Often when one radioactive isotope decays into another, the daughter produces is also unstable and further decays occur until a stable nucleus is created. Such successive decays are said to form a decay series. Because of such decay series, certain radioactive elements are found in nature that otherwise would not exist.

The isotope of uranium-238 undergoes a succession of decays until the stable isotope of lead-206 is created.
HALF-LIFE AND RATE OF DECAY

Although the syllabus does not specifically mention this topic, you can’t appreciate the ideas associated with radioactivity without having a good working knowledge of rates of decay and half-lives of radioactive isotopes.

A macroscopic quantity of any radioactive isotope consists of an enormous number of unstable nuclei. The decay of an individual nucleus is a random event and can’t be predicted. However, in a given period of time, we can predict how many nuclei will decay, by assuming that each nucleus has the same probability of decaying in each second that it exists. The number of decays $\Delta N$ that occur in a very short period of time $\Delta t$ is proportional to the total number of radioactive nuclei present at that instant of time

$$\Delta N = -\lambda N \Delta t$$

The negative sign indicates the number of radioactive nuclei is decreasing and the constant of proportionality $\lambda$ is called the decay constant. Each different isotope has its own unique decay constant. The greater the value of the decay constant, the more decays that occur in a given time interval.

If at a time $t = 0$, there are $N_0$ radioactive nuclei, then at some later time $t$ the number of remaining radioactive nuclei $N$, is given by the radioactive decay law

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

So, the number of radioactive nuclei decreases exponentially with time. The rate of decay is given often specified by its half-life $T_{1/2}$ and the value of the decay constant $\lambda$. The half-life is defined to be the time interval it takes for half the number of the nuclei to decrease by the factor 2.

$$t = T_{1/2} \quad N = N_0 / 2 \quad \Rightarrow \quad (1/2) = e^{\lambda t}$$

$$\Rightarrow \quad T_{1/2} = \ln(2) / \lambda = 0.693 / \lambda \quad \text{natural logarithm } \ln( ) \equiv \log_e( )$$

$$\Rightarrow \quad \lambda = \ln(2) / T_{1/2} = 0.693 / T_{1/2}$$

The longer the half-life of an isotope, the smaller the decay constant, and the more slowly does it decay.

The mean life $\tau$ (average lifetime – on average how long nuclei survive before they decays) of an isotope is given by

$$\tau = \frac{1}{\lambda} = \frac{T_{1/2}}{\ln(2)}$$

The rate of decay $A$ or the number of decays per second is

$$A = \frac{dN}{dt} \quad \text{hence} \quad A_0 = \frac{dN_0}{dt}$$

$$A = A_0 e^{-\lambda t} \quad \text{the activity } A \text{ also decreases exponentially with time}$$

The half-lives of radioactive isotopes vary from as short as $10^{-22}$ s to about $10^{21}$ yr.
The isotope of gas radon $^{222}\text{Rn}_{86}$ decays into the isotope of polonium $^{218}\text{Po}_{84}$ via alpha decay. The energy of the emitted helium nucleus is 5.59 MeV and its half-life is 3.8235 days. Figure (3) shows the exponential decay of radon starting with a sample of 100 g of the gas. The mass of radon gases halves in each successive half-life time interval.

Fig. 3. The exponential decay of radon.
NUCLEAR REACTIONS

It is possible to change the structure of nuclei by bombarding them with energetic particles. Collisions which change the identities of the target nuclei are called nuclear reactions. The first nuclear reaction was performed by Rutherford in 1919 in which a nitrogen target was irradiated with α-particles from a natural radioactive source.

\[ ^4\text{He}_2 + ^{14}\text{N}_7 \rightarrow ^{17}\text{O}_8 + ^{1}\text{H}_1 \]

nuclear transmutation

Nuclear fusion

The process of building up nuclei by bring together individual protons and neutrons or building large nuclei by combining small nuclei is called nuclear fusion.

The mass of every stable nucleus is less than the sum of the masses of its constituent protons and neutrons.

The mass of the helium isotope \(^4\text{He}_2\) is less than the combined mass of its two protons and two neutrons. Thus, if two protons and two neutrons were to come together to form a helium nucleus there would be a loss of mass. This loss in mass is responsible for the release of an enormous amount of energy in this fusion process.

Virtually all the energy of the universe originates in the fusion of hydrogen nuclei into helium nuclei in the interior of stars.

To view the proton-proton cycle which is one of the main fusion processes for producing energy by our Sun, go to

http://burro.astr.cwru.edu/Academics/Astr221/StarPhys/ppchain.html

An interesting web site to visit is:

http://education.jlab.org/index.html