

Nuclear physics

Typed version of the handwritten O Level Physics class notes (18 August to 8 September 2020). The original handwritten pages, with their diagrams, are on the same page of megalecture.com.

The atom

- **Atom:** the smallest part of matter, further divided into 2 parts, the nucleus and the electrons. (Objects → matter → atom → nucleus and electrons; nucleus → nucleons → protons and neutrons.)
- **Nucleus:** the central part of the atom. It consists of nucleons; nucleons are the protons and neutrons in it.
- **Proton:** a particle which lies inside the nucleus and carries a positive charge.
- **Neutron:** a particle which lies inside the nucleus and carries no charge.
- **Electron:** a particle which revolves around the nucleus and carries a negative charge.
- The magnitude of the positive and negative charge on the proton and electron is equal.

Particle	Position	Charge	Mass
proton	inside the nucleus	$+1.6 \times 10^{-19}$ C	1.66×10^{-27} kg
neutron	inside the nucleus	zero	1.66×10^{-27} kg
electron	outside the nucleus	-1.6×10^{-19} C	9.1×10^{-31} kg

Mass number: the total number of protons and neutrons in an atom; also called the nucleon number; represented by the letter A. **Atomic number** (proton number): represented by the letter Z.

Alpha-particle scattering experiment

With the help of this experiment we determine how to describe the structure of the atom. Set-up (top view): a source of α -particles in a lead block, a thin gold sheet (thinner than paper, about 1 micrometre thick), and a movable microscope that can be moved around the full 360° .

- An α -particle is a radioactive particle with a positive charge.
- There are 3 types of radiation: alpha, beta and gamma. None of them can pass through the lead block.
- The source of α -particles is placed in a lead block, and since the radiation cannot move to the sides, it comes out in straight lines.
- α -particles cannot be seen using a microscope: the lens of the microscope is coated with zinc sulphide to detect their presence. When charged particles hit zinc sulphide, a spot of light is produced.

Observations:



1. Most of the α -particles passed undeflected through the gold sheet.
2. Some of the α -particles were deflected while passing through the gold sheet.
3. A few α -particles were deflected in an almost backward direction.

Conclusions:

1. The major part of an atom is empty.
2. The nucleus carries a positive charge.
3. The size of the nucleus is negligible when compared to the size of an atom.

Radioactive decay

Radioactive decay: a process in which an unstable nucleus emits radiation to become stable (normally isotopes that want to stabilise). Also called nuclear decay or radioactivity, because the radiation comes from the nucleus of the element, and the size of the nucleus also reduces because of that (called decay because the size of the element decreases when it emits radiation).

- Nuclei emitting this radiation $\rightarrow$ radioactive elements.
- The emitted radiation $\rightarrow$ radioactive radiation.
- Particles in alpha and beta radiation.

Summary of the three radiations (the three differ in deflection because of their mass, speed and charge; ionisation and penetration go in opposite orders):

Radiation	What it is	Charge	Range in air	Stopped by
α	helium nucleus (2 protons + 2 neutrons, no electrons)	+2	about 5 to 10 cm	paper
β	electron	-1	about 50 cm	aluminium sheet
γ	electromagnetic wave (not a particle; no charge, no mass)	0	infinite	lead block

Radiation	Speed	Ionising power	Deflected by fields?
α	about 10% of c	highest (largest mass)	yes
β	about 90% of c	less than α	yes (more than α : smaller mass, higher speed)
γ	$c = 3 \times 10^8$ m/s	extremely low	no (not charged)

Properties of radioactive decay

1. **Random nature of decay:** radiation randomly comes out of the radioactive element; the number of radiations coming out of the element does not remain constant; their direction cannot be figured out, nor which nucleus will decay first.
2. **Spontaneous process:** the rate of radioactive decay is not affected by a change in physical conditions such as temperature and pressure, or by chemical change.

Radiation in an electric field. A radioactive source is placed in a lead block (the lead block does not allow any radioactive radiation to pass through it, so the radiation only moves in a straight direction) between two charged metal plates. When the radiation passes through the electric field, it splits in 3 directions:

1. Undeflected: gamma.
2. Deflected towards the positively charged plate: beta.
3. Deflected towards the negatively charged plate: alpha.

Radioactive elements can emit 1, 2 or 3 (at most) types of radiation; different elements emit different types of radiation.

Alpha radiation

- Alpha radiation consists of particles which are called alpha particles; alpha radiation comes out of the nucleus of the element.
- Alpha particles consist of two protons and two neutrons (helium): an alpha particle is also called a helium nucleus, represented by the symbol ${}^4_2\alpha$ or ${}^4_2\text{He}$ (mass number 4, atomic number 2).
- Alpha particles have a positive charge as a whole, because there is no electron.
- The mass of an alpha particle is equal to 4 times the mass of a proton.
- The speed of an alpha particle is equal to 1/10 of the speed of light ($c/10$).
- The range of an alpha particle in air is 5 cm (at most they can cover 5 cm in air after being emitted) and it can be stopped by a paper sheet (penetrating power is very low).
- Alpha particles cause ionisation in gases (ionising power is high): when one passes through a gas, it removes an electron from a gas atom (it does not take it) and produces ions. Alpha particles passed through air produce the most ions as compared to beta and gamma rays.
- Ionising power depends on: (i) mass (directly proportional); (ii) speed (inversely proportional).
- Alpha particles are deflected in both electric and magnetic fields (deflection happens because both electric and magnetic fields exert forces on charged particles).

Beta radiation

- Beta radiation comes out of the nucleus; beta particles are electrons. The electrons are not emitted from the shells of the atom: instead one of the atom's neutrons decays into a proton and an electron; the proton stays in the nucleus but the electron is emitted at a high speed, and these are called beta radiation or beta particles.
- A beta particle is represented by the symbol ${}^0_{-1}\text{e}$ or ${}^0_{-1}\beta$.
- A beta particle carries a negative charge. The mass of a beta particle is 1/1840 of the mass of a proton.
- The speed of a beta particle is equal to 9/10 of the speed of light ($9c/10$). A β particle has more kinetic energy than an α particle, and its mass is lower than that of an α particle, which is why a β particle has a higher speed.
- The range of a beta particle in air is 50 cm and it can be stopped using an aluminium sheet (more dense than paper).
- β radiation results in ionisation in air (its ionising power is less than that of α): ionising power depends on mass (directly proportional) and speed (inversely proportional), hence less ionising

power.

- A beta particle is deflected in both electric and magnetic fields.
- Aluminium can stop both α and β , but a paper sheet only works on α .

Gamma radiation

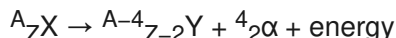
β and α particles have energy but are not energy themselves, while on the other hand gamma rays are a form of energy.

- Gamma radiation is electromagnetic waves; it carries energy (all types of waves carry energy). It is represented by the symbol γ .
- Gamma radiation has no charge and no mass (charge and mass are properties of a particle).
- Gamma radiation travels at the speed of light (all electromagnetic waves travel at the speed of light).
- Its range in air is infinite and it can be stopped by a block of lead: it passes straight through all bodies instead of colliding with them. A lead block will block all 3 radiations because of its very high density.
- Gamma radiation results in ionisation in air (but its ionising power is extremely low).
- Gamma radiation is not deflected by electric or magnetic fields (they deflect charged particles, and gamma has no charge).
- Gamma radiation is harmful to us: it can damage tissues and cause cancer, and can affect or destroy organs (it has high energy and can penetrate through our body).

Radioactive decay equations

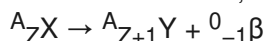
The process is completely random. Three kinds: alpha decay, beta decay, gamma decay. (In a magnetic field beta has more deflection because of its smaller mass and greater speed; in an electric field alpha shows more deflection because it has double the charge of beta.)

1. **Alpha decay:** when an element emits an alpha particle, its mass number decreases by 4 units and its atomic number decreases by 2 units.



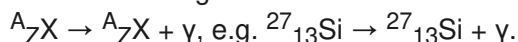
E.g. polonium turns into lead after emitting an α particle: ${}^{208}_{84}\text{Po} \rightarrow {}^{204}_{82}\text{Pb} + {}_2^4\alpha$. (The name changes from X to Y because the atomic (proton) number changes, so the element changes as well.)

2. **Beta decay:** when an element emits a β particle, its mass number remains the same but its atomic number increases by 1 unit, because a neutron splits into a proton and an electron; the electron is emitted, so the proton number increases by 1.



E.g. ${}^{14}_6\text{C} \rightarrow {}^{14}_7\text{N} + {}_{-1}^0\beta$; ${}^{46}_{20}\text{Ca}$ (26 neutrons) $\rightarrow$ ${}^{46}_{21}\text{Sc}$ (25 neutrons) $+ {}_{-1}^0\beta$.

3. **Gamma decay:** when an element emits gamma radiation, its mass number and atomic number remain unchanged.



Gamma decay always happens after alpha and beta decays: the excess energy comes out of the nucleus in the form of gamma radiation.

Geiger–Müller tube (GM tube)

A device which is used to detect the presence of a radioactive source or radioactive radiation is called a GM tube. It is a copper can filled with gas, with a window at one end and a metal rod placed inside the can; the rod is connected to the positive terminal and the copper can to the negative terminal, with a ratemeter in the circuit.

- Radioactive radiation from the radioactive source passes through the window.
- It produces ionisation in the gas: positive ions are attracted to the copper can (connected to the negative terminal), and negative ions are attracted to the metal rod (connected to the positive terminal).
- When negative ions pass through the ratemeter, you hear a click or a beep indicating a number of ions.
- Higher intensity of radioactive radiation → higher reading; lower intensity → lower reading.
- There is always some radioactive radiation around us: to find the actual count you have to take the background count before placing the radioactive source and then a count after placing it.

Q. Where do we get this radiation from? Underground uranium rocks (because of which argon gas is produced and radioactive radiation occurs), granite (a type of marble), the Sun, machines (X-rays, nuclear reactors), our bodies (isotopes of potassium present in food, isotopes of C-14).

- **Background count:** the reading shown by the ratemeter due to the radioactive radiation present around us.
- **Background radiation:** radioactive radiation which is present around us naturally (cosmic rays, polluted air and water, nuclear reactors in the surroundings, the Earth's crust).
- Actual count = count rate – background count.

Half-life

- **Half-life:** the time in which half of the atoms of a radioactive element decay is called the half-life of the radioactive element. (Since the world began, atoms have been decaying; we use the half of the atoms to work out the number of atoms present at the current time.) Half-life is the time it takes for the number of nuclei to decrease by half (the number of atoms is halving).
- All radioactive elements have a fixed half-life, but theirs is different from other elements: it can be in seconds or even in years.
- **Activity:** the overall decay rate of all the isotopes in our sample, measured in becquerels. 1 Bq = 1 decay/second. It is not possible to calculate the half-life of a single isotope, so we use a sample with a large number of the same isotopes. As more and more of the particles decay, the number of unstable particles decreases and so the activity also decreases (e.g. activity 600 → 300 in 2 hours: half-life = the time taken for the activity to halve).

Determination of half-life. A radioactive source is placed under a GM tube connected to a ratemeter.

- The GM tube and the ratemeter are connected.
- Radiation will ionise the gas in the GM tube; the ratemeter detects the ions.
- The reading on the ratemeter is indirectly determining the number of atoms.
- Note the readings after a certain time interval and plot them on a graph: number of atoms

against time is a falling curve.

Nuclide: a fancy name for an atom. **Nucleons:** the collective term for protons and neutrons.

Nuclear fission (in nuclear reactors)

- A process in which a heavy nucleus splits into two light nuclei with the release of energy.
- Two types: (i) spontaneous fission (the natural fission process, on its own or automatically, from an unstable nucleus); (ii) neutron-induced fission (the artificial fission process, by absorbing a slow-moving neutron). It has radioactive products.
- A neutron is projected into uranium, which splits into barium and krypton (the fission fragments) plus neutrons and energy:

$$^{235}_{92}\text{U} + ^1_0\text{n} \rightarrow ^{144}_{56}\text{Ba} + ^{90}_{36}\text{Kr} + 2\ ^1_0\text{n} + \text{energy (sound, heat, radioactive radiation)}$$

The remaining neutrons come out as isolated neutrons along with energy. (The neutrons that come out belonged to the uranium; barium and krypton play no role in that, and the neutron we fired in becomes part of the uranium.)
- **Parent nucleus:** the heavy nucleus that splits into two light nuclei during nuclear fission; the nucleus before the reaction takes place.
- **Daughter nuclei:** the two lighter nuclei that come from the splitting of a heavy nucleus during nuclear fission; the nuclei after the reaction.
- According to Einstein's mass–energy relation, mass can be converted into energy and energy can be converted into mass. Proof: the total mass of Ba and Kr < the mass of U; the remaining mass (the mass defect) converts into energy: **E = mc²** (energy = mass × speed of light squared).
- Nuclear fission is a chain reaction. Nuclear reactors: a controlled chain reaction. Atomic bomb: an uncontrolled chain reaction.

Nuclear fusion (in the Sun and stars)

- A process in which two light nuclei combine to form a heavy nucleus with the release of energy (the reverse reaction of nuclear fission, yet energy is released in both of them).
- Two deuterium nuclei fuse to give a helium nucleus (not a radioactive product) and a neutron:

$$^2_1\text{H} + ^2_1\text{H} \rightarrow ^3_2\text{He} + ^1_0\text{n} + \text{energy}$$
- Total mass before fusion > mass after fusion; the leftover mass is converted into energy.
- Condition: extremely high temperature (needed to overcome the repulsion between the 2 positive nuclei and move them at a very high speed to have them merge: higher temperature = higher energy).
- Stars and suns produce light and heat energy, which happens because of nuclear fusion.

Nuclear reactor

- It is used to produce thermal energy by using a controlled fission reaction. The thermal energy is then used to turn turbines, which then produce electrical energy.
- Parts: (i) fuel rods, (ii) moderator, (iii) control rods, (iv) coolant (CO₂ gas), all inside a concrete shield; water in, steam out.

- Fuel rods are made up of uranium, used to produce the fission reaction.
- They are surrounded by graphite blocks called moderators, used to slow down neutrons (the two extra neutrons produced): slow-moving neutrons are absorbed by uranium, which makes it unstable, and that is what causes the next step.
- Control rods are made up of boron, which can easily absorb neutrons. Strings attached help to move the rods up or down: to increase the rate of reaction, lift the rods to the top; to decrease the rate of reaction, let them down; if brought level with the fuel rods, the reaction stops altogether. In other words, control rods are used to control the fission reaction.
- The coolant circulates inside the nuclear reactor and carries with it the heat produced during the reaction; the heat hits the water pipes and turns the water into steam; the steam is then used to run turbines. Turbines produce electrical energy because they cut magnetic field lines: electromagnetic induction.

Nuclear energy (nuclear reactor) → steam energy (boiler) → kinetic energy (turbine) → electrical energy (generator).

Hazards of radioactive radiation

Radioactive radiation acting on a cell can cause: ionisation (destruction of the cell, burning of the cell); damage to DNA (uncontrollable splitting of the cell, a tumour); damage to a gamete (sperm or egg cell), giving a genetic disorder (also called future mutation).

1. **Contamination:** if a radioactive source gets inside our body and damages the organ tissues or cells, then we say that the body has been contaminated, for example through inhaling the air. The radioactive source, after entering the body, will produce radioactive radiation inside the body.
2. **Irradiation:** if radioactive radiation produced by the radioactive source hits our body and then damages the organ tissues or cells, then we say that the human body has been irradiated. The radiation penetrates the body and gets inside.

Uses of radioactive radiation

1. **Thickness measurement.** Paper from the paper plant passes between a radioactive source and a GM tube connected to a ratemeter. If the ratemeter shows a constant reading throughout, the paper has a uniform thickness throughout.
2. **Smoke detector.** The alarm circuit produces a current that would make the alarm ring; when radiation from the radioactive source falls on the detector, it produces a current as well; the current from the detector cancels out the current from the alarm circuit, so the bell does not receive current and does not ring. In case of fire, there is smoke: the smoke comes between the radioactive source and the detector, resulting in no current produced by the detector, because the smoke blocks the radiation from reaching the detector. Since the current produced by the alarm circuit is not cancelled out, the alarm rings.
3. **Medical diagnosis.** A radioactive chemical is injected into the desired tissue or organ; using a special camera an image is produced with the help of the radiation, which helps to identify the problem.
4. **Radiation therapy.** Gamma rays are directed towards a tumour and they destroy it.

5. **Food irradiation.** Microbes (almost invisible bacteria) decay food and can be destroyed using radioactive radiation of low intensity.
6. **Sterilisation.** Place the medical instrument in a plastic bag and direct radioactive radiation towards it.
7. **Fault detection.** For example, if you weld two pipes and wrap photographic film around the weld, then place a radioactive source inside the pipe, the radiation will darken the film. If the film darkens, there is a flaw in the welding (film wrapped around the pipe, radioactive source in the pipe); if it does not darken, there are no flaws.
8. **Carbon dating.** Carbon has 3 isotopes: $^{12}_6\text{C}$ and $^{13}_6\text{C}$ are stable; $^{14}_6\text{C}$ is unstable, a radioactive isotope. Every living thing takes in carbon (^{12}C and ^{14}C); when they die, they stop. For example, in a dead animal the amount of ^{12}C taken in remains the same after death, while the ^{14}C decays; comparing the mass of the two tells us when the death took place. The half-life of $^{14}_6\text{C}$ is about 5,700 years.

Precautions for handling radioactive sources and radiation

- Store radioactive material in a lead box.
- Wear lead-lined gloves and suits in radioactive labs.
- Move the radioactive material with tongs and forceps.
- Avoid drinking and eating during a lab experiment with radioactive nuclei.
- Hang radioactive precautionary symbols in the region where radiation is present.

Star formation

- A star is formed out of a cloud of cool, dense molecular gas. In order for it to become a potential star, the cloud needs to collapse and increase in density.
- For this to happen, it can either collide with another dense molecular cloud, or it can be near enough to encounter the pressure caused by a giant supernova. Several stars can be born at once with the collision of two galaxies.
- In both cases, heat is needed to fuel this reaction, which comes from the mutual gravity pulling all the material inward.
- What happens next depends upon the size of the newborn star, called a protostar. Small protostars will never have enough energy to become anything but a brown dwarf. Medium to large protostars can take one of two paths depending upon their size: if they are smaller than the Sun, they undergo a proton–proton chain reaction to convert hydrogen to helium; if they are larger than the Sun, they undergo a carbon–nitrogen–oxygen cycle to convert hydrogen to helium. The difference is the amount of heat involved: the CNO cycle happens at a much higher temperature.
- Whatever the route, a star has been formed. The life cycle of a star depends upon how quickly it consumes hydrogen: for example, small red dwarf stars can last hundreds of billions of years, while large supergiants can consume most of their hydrogen within a comparatively short few million years. Once the star has consumed most of its hydrogen, it has reached its mature state. This is how a star forms.

Checked by Mega Lecture

This typed version follows the handwritten notes. Corrections: the mass of a beta particle is written as $1/1840$ of a proton's mass (the notes say "1840 times"); the half-life of carbon-14 is written as about 5,700 years (the notes say 5,400); the hazards diagram and the apparatus sketches (scattering experiment, electric-field plates, GM tube, reactor, thickness gauge) are described in words. The Urdu side notes are given in English. Spotted a mistake? Tell us on WhatsApp: +92 336 780 1123.