

## RADIOACTIVITY and ITS APPLICATIONS

### **Introduction:**

The nucleus of an atom contains the protons and neutrons. Virtually all the mass of the atom is concentrated in the nucleus, because the electrons weigh so little.

The number of protons is called the **atomic number (Z)**. The number of protons and neutrons in the nucleus of an atom is called the **mass number (A)**. The mass number is also called the **nucleon number**.

**Nuclides and isotopes:** A **nuclide** is an atomic specie whose atomic number and mass number are specified.

Nuclides are written as  ${}^A_ZX$

Where **A** is the mass number, **Z** is the atomic number and **X** is the number of the atomic species.

The species  ${}^{12}_6C$  and  ${}^9_4Be$  are nuclides of elements carbon and beryllium.

Protons, neutrons, electrons are also nuclides represented as nuclides  ${}^1_1P$  ( ${}^1_1H$ ),  ${}^1_0n$  and  ${}^0_{-1}e$  respectively.

**Isotopes** are atoms of the same element with the same atomic number but different mass numbers. Isotopes differ in terms of neutrons in these nuclei e.g.

a) Chlorine has 2 isotopes.

Chlorine-35, ( ${}^{35}_{17}Cl$ ) with **18** neutrons and Chlorine-37, ( ${}^{37}_{17}Cl$ ) with **20** neutrons

b) Carbon has three isotopes namely;

Carbon-12, ( ${}^{12}_6C$ ) with 6 neutrons; Carbon-13, ( ${}^{13}_6C$ ) with 7 neutrons and Carbon, ( ${}^{14}_6C$ ) with 8 neutrons.

**An isotope** is an atom of an element that has the same atomic number but different mass number with another atom of the same element.

**Isotopy** is the existence of atoms of an element with the same atomic number but different mass numbers.

**Definition:** Radioactivity is the **spontaneous disintegration/decay/breakdown of heavy, unstable nuclei of atoms to form lighter and stable nuclei** with the **emission of radiations** such as alpha particles, beta particles and gamma rays together with energy. It is sometimes referred to as **Natural Radioactivity** and the process is known as **Radioactive decay**.

An isotope whose nucleus undergoes radioactive decay is called a **radioactive isotope** or **radio isotope**.

### Properties of Radioactive Emissions/Radiations/Rays

#### (a) **Alpha ( $\alpha$ ) particles/rays/emissions/radiations.**

An alpha particle is a helium nucleus emitted during radioactive decay with mass number (atomic mass) of 4 and atomic number of 2. i.e. It is written as  ${}^4_2He$ .

Alpha particles have the following properties:

- Have a mass number of 4 units and a charge number of +2 each.
- Their speed is about one to one twentieth of the speed light, ( $\frac{1}{120} \times 3 \times 10^8$ ).
- They are deflected by both electric and magnetic fields. In an electric field, they are deflected towards the negative plate because they are positively charged.
- They have a very low penetrating power (their relative penetrability is 1). This is because of their large mass and relatively low speed. They can be absorbed or stopped by a sheet of paper and a few cm of air.
- They have a very high ionizing power (their relative ionizing power is 10,000). They cause ionization of gases. This is because they are positively charged and so they can attract **electrons** from the **atoms** they get into contact with and cause loss of electrons.
- They can cause fluorescence in some materials.
- They cause heating effect in metals.
- They blacken photographic plates.

During alpha decay, the atomic number decreases by 2 and atomic mass decreases by 4.



**1<sup>st</sup> Law of radioactivity.** It states that “when an element disintegrates by emission of an alpha particle, it turns into an element with chemical properties similar to those of an element two places earlier than it in the Periodic Table”.

**(b) Beta ( $\beta$ ) particles/rays/emissions/radiations.**

A beta particle is an intra-nuclear electron emitted when a neutron is converted into a proton. A beta particle is written as;  ${}_{-1}^0e$  or  ${}_{-1}^0\beta$   ${}^1_0n \longrightarrow {}^1_1H + {}_{-1}^0e$

However, a beta particle is not the ordinary electron of atoms. Beta particles have the following properties:

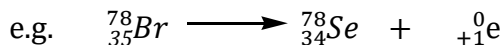
- They have negligible mass i.e their mass is approximately zero.
- They are negatively charged and have a charge number of -1.
- They are deflected by both electric and magnetic fields. In an electric field, they are deflected towards the positive plate because they are negatively charged. They are deflected more than alpha particles because they are lighter.
- Their speed varies from 3% to 99% of the speed of light.
- They have a high penetrating power. They are more penetrating than the alpha particles because they move faster and have a negligible mass hence, they can penetrate a few mm of aluminium foil.
- They have a lower ionizing power than alpha particles (their relative ionizing power is 100) because they have a negligible mass and move faster.
- They blacken photographic plates.

In beta decay, mass number is not affected but the atomic number increases by 1.



**2<sup>nd</sup> Law of radioactivity.** It states that “when an element disintegrates by emission of a beta particle, it turns into an element with chemical properties similar to those of an element one place later in the Periodic Table”.

A **positron** is taken as a positively charged beta particle ( $+\beta$ ) written as  ${}_{+1}^0e$  or  ${}_{+1}^0\beta$



**(c) Gamma ( $\gamma$ ) particles/rays/emissions/radiations.**

Gamma rays are extra or excess energies the nucleus releases or gives out as it gains stability after radioactive decay or disintegration. Sometime after the emission of either  $\alpha$  or  $\beta$  particles, the residue (atomic species being formed) remains with a lot of energy which leaves it in an excited state. They simply constitute excess energy and have no effect on mass and atomic number.

During radioactivity, stability (or the ground state) is attained when a radioisotope releases excess energy in form of electromagnetic radiations called gamma rays.

Gamma rays are not material particles and are represented as;  $\gamma$  or  ${}^0_0\gamma$ .

They have the following properties:

- They have zero mass and zero charge.
- They are not deflected by both electric and magnetic fields because they are not charged.
- They have a very high penetrating power and hence can penetrate a few cm of lead metal. i.e. They have a higher penetrating power than beta particles. This is because the gamma radiations have no mass hence moving at a high speed.
- They have a very low ionizing power.
- They travel at a speed of light.
- They have high energy electromagnetic radiations of very short wave length.

**Other particles** that may be emitted during radioactivity include the:

- Proton p, written as  ${}^1_1H$
- Neutron n, written as  ${}^1_0n$
- Deuterium particle d, written as  ${}^2_1H$

- Tritium particle t, written as  ${}^3_1\text{H}$

### The Effects of Radioactive Emissions on the Nucleus of an Atom

(a) When an atom or a nucleus emits an alpha particle, its mass number decreases by **four units** and its atomic number decreases by **two units**. This is illustrated in the nuclear reaction equation below;



(b) When an atom or a nucleus emits a beta particle, its mass number **remains unchanged or constant** but its atomic number increases by **one unit** as illustrated in the nuclear reaction equation below;



(c) When an atom or a nucleus emits gamma rays, its mass number and atomic number **remain constant or unchanged**.  ${}^{60}_{27}\text{Co} \longrightarrow {}^0_0\gamma + {}^{60}_{27}\text{Co}$

### Detection and measurement of radiations

Methods of detection and measurement of radiations include:

(a) Use of measuring instruments like Geiger Muller Counter (H.Geiger and F.M.Muller invented a device that enable particles emitted in radioactive decay to be counted as pulses of electric current) and the Wilson Cloud Chamber (The tracks of condensation produced by ionizing radiation in the Wilson Cloud Chamber can be photographed).

(b) Use of photographic plate. A photographic film is exposed to radioactivity.

(c) Scintillation Counter. These are substances such as zinc sulphide which phosphoresce when affected by radioactivity. A particle from a radioactive source hits the phosphor and a flash of light is emitted giving rise to a pulse of current recorded by a digital counter.

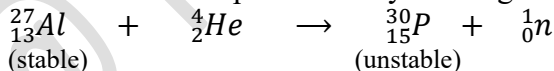
### Artificial (Man-Made) Radioactivity

It was first discovered by **Irène Joliot-Curie** and **Frédéric Joliot-Curie** in **1934**.

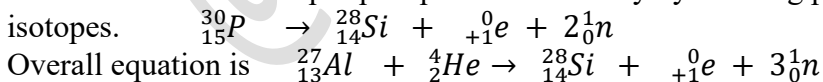
If a substance emits a radiation by itself, it is said to possess natural radioactivity, but if a substance is non-radioactive (stable) and starts to emit radiations, after exposure to rays or particles from a natural radioactive substance, then it is said to possess induced or artificial radioactivity. Thus, when a stable nucleus is bombarded by particles, the nucleus becomes heavy and unstable. The instability is **caused** by either an excess of protons or an excess of neutrons.

**Artificial radioactivity** is the induced disintegration of naturally occurring stable nuclides through bombardment with fast moving particles (neutrons, protons, alpha particles) forming more stable nuclides with emission of radiations and energy. It can also be defined as the spontaneous disintegration of nuclei of unstable isotopes that have been made by man through bombardment of naturally occurring stable (non-radioactive) isotopes with emission of protons, neutrons, gamma rays, alpha, beta particles. e.g.

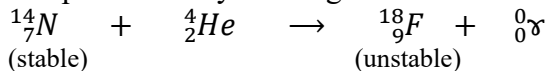
(a) when stable isotopes of aluminium are bombarded with alpha ( $\alpha$ ) particles, artificial radioisotopes of phosphorous are formed which spontaneously disintegrate as illustrated below:



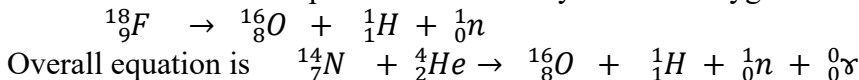
The artificial radioisotopes phosphorous-30 decay by emitting positrons and neutrons to form silicon-28 isotopes.



(b) when stable isotopes of nitrogen are bombarded with alpha ( $\alpha$ ) particles, artificial radioisotopes of fluorine are formed which spontaneously disintegrate as illustrated below:



The artificial radioisotope fluorine-18 decays to form oxygen-16 with emission of a proton and a neutron.





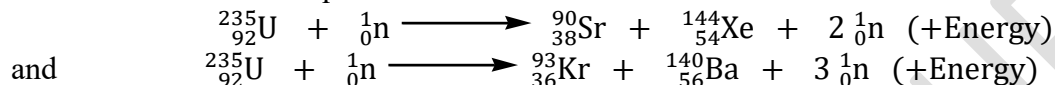
Certain nuclear fissions can also be induced by protons, deuterium particles or alpha particles but the most important are those that are brought by neutrons.

**Note:** During nuclear fission;

- There is production of new neutrons at great speed which may collide with other atoms of the same element to produce other neutrons and the process may continue until all atoms of the element are split up. This leads to a chain reaction.
- There is evolution of a very large amount of energy.

When an element splits up, the combined masses of particles formed are less than the original mass. The balance is transformed into energy as with Einstein's law.  $E = mc^2$ .

For example; there are two possible fissions of Uranium-235 isotope when it's bombarded with neutrons as shown in the nuclear reaction equations below:



Each time a nucleus of Uranium-235 is split, there is loss in mass which is converted into energy by Einstein's equation or law.  $E = mc^2$ .

e.g. for conversion of 1g of mass into energy,  $E = 1 \times 10^{-3} \times (3 \times 10^8)^2 \text{ J} = 9 \times 10^{10} \text{ kJ}$

The energy derived from nuclear fission has been applied into ways: -

- In nuclear/atomic bombs where the output of energy is uncontrolled, the large amount of energy released when a nuclear bomb explodes is derived from the extremely rapid chain reaction involving fission of a few pounds of Uranium-235 and Plutonium-239 isotopes.
- Nuclear/Atomic Power Plants which produce electricity from nuclear energy obtained from nuclear fission. In this case, the output energy is controlled.

**Note that;** natural radioactivity is shown by elements with atomic number greater than 83 while artificial radioactivity can be induced in elements with atomic number less than 83.

### Balancing Nuclear Equations

The following rules are applied when balancing nuclear reaction equations.

- The sum of mass number for the reactant species (nuclides) must be equal to the sum of the mass number for the product species.
- The sum of the charge number (atomic number) for the reactant species or nuclides and that for the product species must be equal.

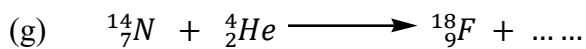
i.e. In an equation for a nuclear reaction, the sum of the nucleon numbers (mass numbers) is the same on both sides and so does the sum of the proton numbers (atomic numbers)

The new nucleus formed is deduced from its atomic number and not the mass number.

**The types of nuclear reactions to be balanced usually apply as follows:**

1. From symbolic nuclear equations; complete the following nuclear reactions.

- ${}_{11}^{24}\text{Na} \longrightarrow \dots\dots\dots + {}_{-1}^0\text{e}$
- ${}_{5}^{10}\text{B} + \dots\dots\dots \longrightarrow {}_{7}^{13}\text{N} + {}_0^1\text{n}$
- ${}_{83}^{218}\text{Bi} \longrightarrow \dots\dots\dots + \dots\dots\dots + 2 {}_2^4\text{He} + {}_{82}^{206}\text{Pb}$
- ${}_{17}^{35}\text{Cl} + {}_0^1\text{n} \longrightarrow {}_1^1\text{H} + \dots\dots\dots$
- ${}_{92}^{235}\text{U} + {}_0^1\text{n} \longrightarrow {}_{36}^{93}\text{Kr} + \dots\dots\dots + {}_{56}^{140}\text{Ba}$
- ${}_{15}^{30}\text{P} \longrightarrow {}_{14}^{30}\text{Si} + \dots\dots\dots$



2. From word nuclear equations; write balanced equations for each of the following nuclear transformations.

(a) Loss of an alpha particle by  ${}^{230}_{90}Th$

.....

(b) Beta decay by lead-214

.....

(c) Fusion of  ${}^{15}_7N$  with a proton to give another nucleus with emission of an alpha particle.

.....

(d) Fusion of sodium-23 and a neutron to give another nucleus with emission of gamma rays.

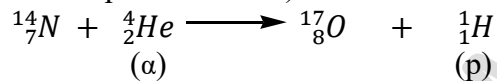
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3. From briefly represented symbolic nuclear equations; write balanced equations from the following nuclear transformations.

(a)  ${}^{14}_7N (\alpha, p)$

In this reaction, an alpha particle collides with an isotope of nitrogen-14 to produce a proton.

(i.e alpha capture and proton release)



(b)  ${}^{16}_8O (p, \alpha)$  reaction (i.e. p capture,  $\alpha$  release)

.....

(c)  ${}^{16}_8O (2n, \alpha)$

Two neutrons collide with an isotope of oxygen-18 to produce an alpha particle

.....

(d)  ${}^9_4Be (2\alpha, 3n)$

.....

4. From radioactive decay series.

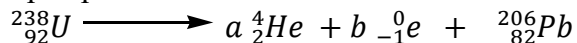
**Radioactive decay series** is a sequence of several nuclear reactions involving loss of alpha, beta and gamma particles leading to formation of stable isotopes. In a decay series, unstable intermediate nuclides are formed.

There are four naturally occurring series of radioactive elements namely:

(a) **The Uranium series.** This starts with Uranium-238 isotope ( ${}^{238}_{92}U$ ) decaying through a series of unstable isotopes up to a stable isotope of ( ${}^{206}_{82}Pb$ ) lead-206.

Qn: Calculate the number of alpha and beta particles emitted in the Uranium decay series.

Let a = number of alpha particles emitted and b = number of beta particles emitted.

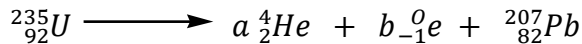


$238 = 4a + 0 + 206$	$92 = 2a - b + 82$
$238 = 4a + 206$	$92 = (2 \times 8) - b + 82$
$238 - 206 = 4a$	$92 = 16 - b + 82$
$a = 8$	$b = 6$

(b) **The Thorium series.** This starts with Thorium-232 isotope to a stable isotope of lead-208.

Qn: Calculate the number of alpha and beta particles emitted in the thorium decay series.

(c) **The Actinium series.** This starts from Uranium-235 isotope to a stable isotope of lead-207 ( ${}^{207}_{82}\text{Pb}$ )



Qn: Calculate the number of alpha and beta particles emitted in the Actinium decay series.

$235 = 4a + 0 + 207$	$92 = 2a + -b + 82$
$235 - 207 = a$	$92 = 2a - b + 82$
$28/4 = 4a/4$	$92 = 2 \times 7 - b + 82$
$a = 7$	$b = 4$

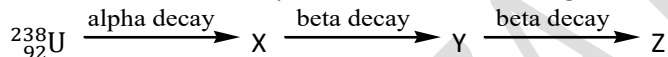
(d) **The Neptunium series.** This starts from Neptunium-237 isotope to a stable isotope of lead-209.

Qn: Calculate the number of alpha and beta particles emitted.

**Sample items:**

1. A team of young Ugandan scientists is working with the Atomic Energy Council to study naturally occurring radioactive materials found in rocks from western Uganda. During their investigation, they discover that some of these rocks contain uranium and thorium, which undergo a series of radioactive decays before becoming stable elements. The scientists set up an experiment to trace the transformation of these elements and record the intermediate products formed during the decay processes.

In one experiment, they observe a sample of uranium-238 undergoing a sequence of decay steps, forming three unknown intermediate products before reaching a more stable form. They represent the process as:



In another experiment, they study thorium-232 and observe a longer decay pathway involving several intermediate products. This process is summarized as:



**Task:** As a student studying nuclear chemistry, you are asked to assist the team in interpreting their results.

Using your knowledge of radioactive decay processes, identify the identities of:

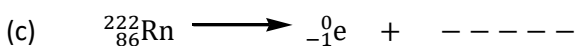
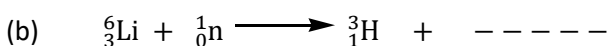
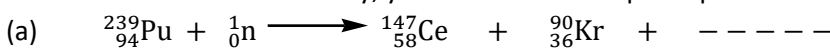
(a) X, Y, and Z in the uranium decay series.

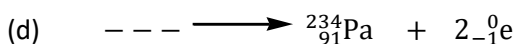
(b) L, M, W, X, and Z in the thorium decay series.

2. At the Uganda Industrial Research Institute, a group of senior students is visiting the nuclear science laboratory to understand how radioactive materials are used in energy production, medicine, and research. During the session, the lead scientist explains that nuclear reactions must obey the principles of conservation of mass number and atomic number.

To assess the students' understanding, the scientist provides several incomplete nuclear equations observed during experiments involving radioactive decay and nuclear fission. The students are required to carefully analyze each reaction and determine the missing particles or nuclei.

**Task:** As a learner of chemistry, you are asked to help complete the following nuclear equations correctly:





For each of the nuclear equations above, determine the missing particle or nuclide. Clearly show how the laws of conservation of nucleon number and charge are applied in each case.

### Differences between nuclear and chemical reaction

- Nuclear reactions involve **fission** for **splitting** or **fusion of nuclei** while chemical reactions **involve transfer (loss or gain) or sharing of electrons**.
- Nuclear reactions result into **formation of new elements** while chemical reactions result into **formation of new compounds**.
- Nuclear reactions are **exothermic i.e. release energy** while chemical reactions can be **exothermic or endothermic**.
- Nuclear reactions **release very large amounts of energy** while chemical reactions **release or absorb smaller amounts** of energy.
- Nuclear reactions produce **radioactive emissions** in the **form of alpha, beta and gamma emissions**.
- The rate of nuclear reactions is not affected by changes in temperature and pressure but rates of chemical reactions are affected by changes in temperature and pressure.
- In nuclear reactions, the isotopes of an element react differently whereas isotopes of an element react in the same way during chemical reactions.

### Radioactive Decay Law

The rate at which a radioactive isotope decays (disintegrations) cannot be speeded up (faster) or slowed down (slower) by any physical or chemical means. It depends only on the:

- identity of the isotope i.e. it is a characteristic of the radio isotope.
- amount (mass, activity, concentration, count rate, number of undecayed atoms) of the isotope present.

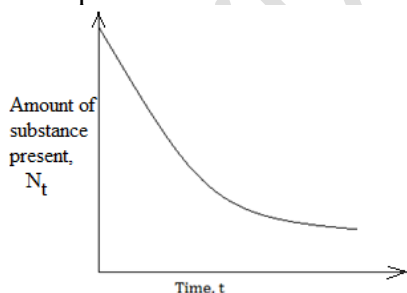
Therefore, the **radioactive decay law states that**; the rate of decay of a radioactive isotope is directly proportional to the amount of the isotope present at that particular time.

Thus, if  $N_t$  = amount of the radioactive isotope present at time  $t$ ,

Then rate of decay  $\propto N_t$

### Graph type 1

Plotting a graph of amount of a radioactive substance present,  $N_t$  against time,  $t$  gives a curve with a negative gradient / slope. This curve is called a **decay curve**.



### Graph type 2

Since amount of the radioactive isotope decreases with increase in time, the change ( $\delta N$ ) is negative because the original amount,  $N_0$  is greater than  $N_t$ . i.e.  $\delta N = N_t - N_0 = \text{negative value}$ .

$$\text{Thus, rate of decay} = -\left(\frac{dN}{dt}\right) \quad \text{Hence} \quad -\left(\frac{dN}{dt}\right) \propto N_t \quad -\left(\frac{dN}{dt}\right) = \lambda N_t \text{ ----- (a)}$$

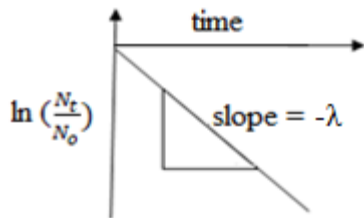
where  $\lambda = \text{decay constant}$ . By definition the decay constant is the constant of proportionality in the decay equation (or this is the fraction of radioactive nuclei which decays per a time).

Equation (a) **is the radioactive decay equation** which can be solved by separating variables followed by integration to form the **integrated rate equation** below:

$$\ln\left(\frac{N_t}{N_0}\right) = -\lambda t \quad \text{----- (i)}$$

which is in the form  $y = m x$

Plotting a graph of  $\ln\left(\frac{N_t}{N_0}\right)$  against time gives a straight line with a negative gradient.



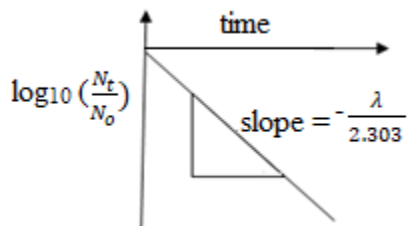
### Graph type 3

Also  $\frac{N_0}{N_t} = e^{-\lambda t}$  then  $N_0 = N_t e^{-\lambda t}$  ----- (ii)

Using logarithm,  $\log_{10}\left(\frac{N_t}{N_0}\right) = -\frac{\lambda}{2.303} t$  ----- (iii)

which is in the form  $y = m x$

Plotting a graph of  $\log_{10}\left(\frac{N_t}{N_0}\right)$  against time gives a straight line with a negative gradient.

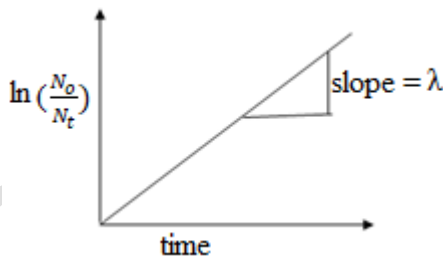


### Graph type 4

If the negative sign is removed,  $\ln\left(\frac{N_0}{N_t}\right) = \lambda t$  ----- (iv)

which is in the form  $y = m x$

Plotting a graph of  $\ln\left(\frac{N_0}{N_t}\right)$  against time gives a straight line passing through the origin and having a positive gradient.



### Graph type 5

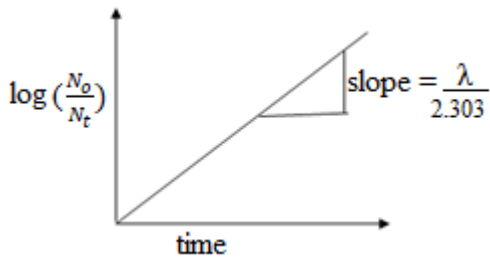
Also  $\frac{N_0}{N_t} = e^{\lambda t}$  then  $N_0 = N_t e^{\lambda t}$  ----- (v)

Using  $\log_{10}$ ,  $2.303 \log_{10}\left(\frac{N_0}{N_t}\right) = \lambda t$  ----- (vi)

$$\log_{10}\left(\frac{N_0}{N_t}\right) = \frac{\lambda}{2.303} t$$

which is in the form  $y = m x$

Plotting a graph of  $\log_{10}\left(\frac{N_0}{N_t}\right)$  against time gives a straight line passing through the origin and having a positive gradient.



All the equations (i), (ii), (iii), (iv), (v), (vi) are referred to as different forms of the **integrated radioactive decay equation**.

**Graph type 6**

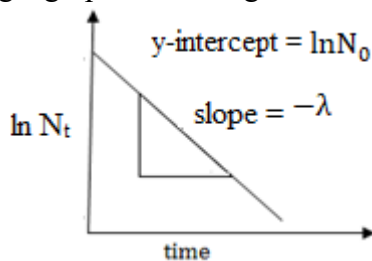
From  $\ln\left(\frac{N_0}{N_t}\right) = \lambda t$  rearranging gives  $\ln N_0 - \ln N_t = \lambda t$

$-\ln N_t = \lambda t - \ln N_0$        $\ln N_t = -\lambda t + \ln N_0$   
 which is in the form  $y = m x + c$

or  $\ln\left(\frac{N_t}{N_0}\right) = -\lambda t$        $\ln N_t = -\lambda t + \ln N_0$

which is in the form  $y = m x + c$

Plotting a graph of  $\ln N_t$  against time gives a straight line with a negative gradient and a y-intercept.



**Graph type 7**

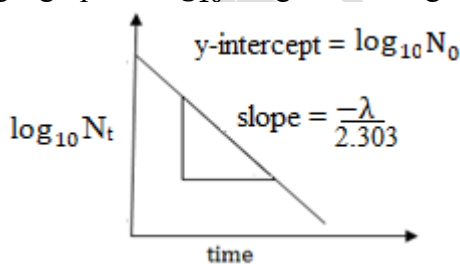
Using  $\log_{10}$ ,  $2.303 \log_{10}\left(\frac{N_0}{N_t}\right) = \lambda t$        $\log_{10}\left(\frac{N_0}{N_t}\right) = \frac{\lambda}{2.303} t$

rearranging gives  $\log_{10} N_0 - \log_{10} N_t = \lambda t$   
 $-\log_{10} N_t = \lambda t - \log_{10} N_0$        $\log_{10} N_t = -\lambda t + \log_{10} N_0$   
 which is in the form  $y = m x + c$

or  $\log_{10}\left(\frac{N_t}{N_0}\right) = -\lambda t$        $\log_{10} N_t = -\lambda t + \log_{10} N_0$

which is in the form  $y = m x + c$

Plotting a graph of  $\log_{10} N_t$  against time gives a straight line with a negative gradient and a y-intercept.



**Half Life ( $t_{1/2}$ ) of a Radioisotope**

This is the time taken for one half of the original amount to disintegrate decay.

It is the time taken for a given amount of a radioisotope to disintegrate to a half its original value.

**Either;** from  $\ln\left(\frac{N_0}{N_t}\right) = \lambda t$       when  $t = t_{1/2}$  and  $N_t = \frac{N_0}{2}$

then by substituting;  $\ln\left(\frac{N_0}{\frac{N_0}{2}}\right) = \lambda t_{1/2}$        $\ln 2 = \lambda t_{1/2}$        $t_{1/2} = \frac{\ln 2}{\lambda}$  ----- (g)

or from  $2.303 \log_{10} \left( \frac{N_0}{N_t} \right) = \lambda t$  when  $t = t_{1/2}$  and  $N_t = \frac{N_0}{2}$  then  $2.303 \log_{10} \left( \frac{N_0}{\frac{N_0}{2}} \right) = \lambda t_{1/2}$

$$2.303 \log_{10} 2 = \lambda t_{1/2} \quad t_{1/2} = \frac{2.303 \log_{10} 2}{\lambda} \text{----- (h)} \quad t_{1/2} = \frac{0.693}{\lambda} \text{----- (i)}$$

Equations (g), (h) and (i) are the same.

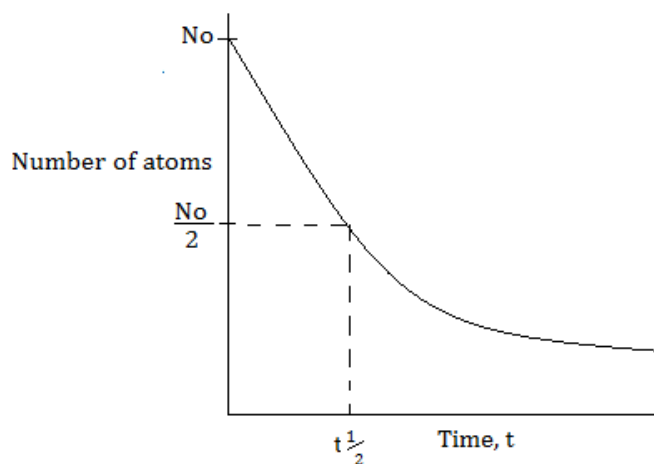
From the above equations for half-life (equations g and h) it is clear that the half-life of a radio isotope is a constant and is independent of the initial amount of the radioisotope. i.e. It is always the same whatever the original amount of the same radioactive substance may be.

The half-life of a radioisotope is an indicator of the stability of the radioisotope. i.e. the longer the half-life, the more stable the radio isotope and the shorter the half-life the less stable the radio isotope.

The table below shows half-life of some radio isotopes

Isotope	Half-life
Lawrencium – 275	8 seconds
Nobelium – 253	10 minutes
Molybdenum – 256	1.5 hours
Phosphorous – 32	14.3 days
Carbon – 14	5570 years

Finding half-life from a graph;



#### Sample items:

1. In a rural community in Uganda, a group of learners participating in a heritage conservation project visit an archaeological site where the remains of an ancient wooden structure have been discovered. The learners are guided by a team of scientists who are studying the history of the site to better understand the lives of people who lived there long ago.

During the investigation, a small piece of the ancient wood is carefully collected and taken to a laboratory for analysis. The scientists explain that they will use carbon-14 dating to estimate how long ago the tree from which the wood came was cut down. They further explain that living trees continuously absorb carbon, including a small amount of carbon-14, but once the tree is cut, the carbon-14 begins to decay at a constant rate.

In the laboratory, the learners observe that the activity of carbon-14 in the ancient wood sample is measured at 10 counts per minute per gram ( $10 \text{ C min}^{-1} \text{ g}^{-1}$ ). For comparison, a sample of freshly cut wood from the same type of tree shows an activity of 15 counts per minute per gram ( $15 \text{ C min}^{-1} \text{ g}^{-1}$ ). The scientists remind the learners that the half-life of carbon-14 is 5600 years.

**Task:** Use this information to help the learners who are challenged to apply their knowledge of radioactive decay to determine the approximate age of the ancient wooden sample.

#### Possible response:

Let original activity be =  $A_0 = 15 \text{ C min}^{-1} \text{ g}^{-1}$

activity at time t be =  $A_t = 10 \text{ C min}^{-1} \text{ g}^{-1}$

half-life be =  $t_{1/2}$  = 5600yrs

age of ancient wood =  $t$  = ?

$$\ln\left(\frac{A_t}{A_0}\right) = \lambda t$$

From radioactive decay equation,

$$\text{but } t_{1/2} = \frac{\ln 2}{\lambda} \quad \lambda = \frac{\ln 2}{t_{1/2}} \quad \lambda = \frac{\ln 2}{5600} = 1.24 \times 10^{-4} \text{ year}^{-1}$$
$$\text{then } \ln\left(\frac{10}{15}\right) = -\left(1.24 \times 10^{-4}\right)t \quad t = 3,270 \text{ years.}$$

2. At Uganda National Bureau of Standards, a team of scientists is conducting a long-term environmental safety study on radioactive materials. One of the elements under observation is Radium, which is known for its slow rate of decay and potential health risks if not properly managed.

A senior laboratory technician explains to a group of learners that radium undergoes radioactive decay over time, and its rate of decay is measured using a concept called half-life. The technician further notes that radium has a half-life of 1590 years, meaning that after every 1590 years, only half of the original radioactive material remains.

To help the learners understand the implications of this, the team places a sealed sample of radium in a controlled storage unit and begins tracking its activity over many years. The goal is to determine how long it would take for the activity of the sample to reduce significantly, ensuring it reaches a safer level for handling and disposal.

As part of their assignment, the learners are asked to apply their knowledge of radioactive decay to analyze the situation.

**Task:** As a chemistry student, determine how long it will take for the activity of the radium sample to decrease to 10% of its original value?

**Possible response:**

$$t_{1/2} = 1590 \text{ years} \quad A_0 = ? \quad A_t = \frac{10}{100} \text{ of } A_0 = \frac{A_0}{10}$$
$$\text{From } t_{1/2} = \frac{\ln 2}{\lambda} \quad \lambda = \frac{\ln 2}{t_{1/2}} \quad \lambda = \frac{\ln 2}{1590} = 4.36 \times 10^{-4} \text{ year}^{-1}$$
$$\text{then using } \ln\left(\frac{A_t}{A_0}\right) = -\lambda t \quad \ln\left(\frac{A_0/10}{A_0}\right) = -(4.36 \times 10^{-4}) \times t \quad t = 5281 \text{ years}$$

3. Isotope  ${}^{60}_{27}\text{Co}$  has half-life 5.27 years. What amount of a 0.01g of  ${}^{60}_{27}\text{Co}$  remains after 1.0 years?

$$\lambda = \frac{0.693}{t_{1/2}} = \frac{0.693}{5.27} = 0.132 \text{ yr}^{-1}$$
$$\text{using } {}_{2.303} \log_{10} \left(\frac{N_t}{N_0}\right) = -\lambda t \quad \log_{10} \left(\frac{N_t}{N_0}\right) = \frac{-\lambda t}{2.303} = \frac{(0.132 \text{ yr}^{-1} \times 1.0 \text{ yr})}{2.303} = 0.0574$$
$$\log_{10} \left(\frac{N_t}{N_0}\right) = 0.0574 \quad \frac{N_t}{N_0} = e^{-0.0574} \quad \frac{N_t}{N_0} = 0.877$$
$$N_t = N_0 \times 0.877 \quad N_t = 0.01 \times 0.877 \quad N_t = 0.00877 \text{ g}$$

3. A team of geologists from Makerere University is conducting research in the rocky highlands of Karamoja to determine the age of ancient rock formations. During their study, they collect a rock sample suspected to contain radioactive elements. Laboratory analysis reveals that the rock contains both uranium-238 and its decay product, lead-206.

The scientists explain that uranium-238 gradually decays into lead-206 over time, and this process can be used to estimate the age of rocks. They further note that the half-life of uranium-238 is  $1.4 \times 10^{17}$  seconds.

In one particular sample weighing 1.0g, the ratio of lead-206 to uranium-238 is found to be 5:1 by weight.

**Task:** As a chemistry learner, using your knowledge of radioactivity and atomic structure:

(a) Find out the number of atoms of lead-206 present in the 1.0 g rock sample.

(b) Estimate the age of the rock sample.

**Possible Response:**

(a) Number of Pb-206 atoms in 1.0 g of rock.

Given ratio by weight: Pb : U = 5 : 1

In 1.0 g rock:

$$\text{mass of Pb} = \left(\frac{5}{6} \times 1.0\right)\text{g} \approx 0.833\text{g}$$

$$\text{mass of U} = \left(\frac{1}{6} \times 1.0\right)\text{g} \approx 0.167\text{g}$$

$$\text{Moles of Pb-206 in 1.0 g rock} = \frac{0.833}{206} \approx 4.0437 \times 10^{-3} \text{ moles}$$

Number of Pb-206 atoms:

1 mole of Pb-206 contains  $6.022 \times 10^{23}$  atoms

$$4.0437 \times 10^{-3} \text{ moles of Pb-206 contains} = 4.0437 \times 10^{-3} \times (6.022 \times 10^{23}) = 2.4351 \times 10^{21} \text{ atoms}$$

(b) Age of the rock.

Key idea: All Pb-206 atoms in the rock came from decay of U-238 atoms.

If N = number of U-238 atoms now, and D = number of Pb-206 atoms now, then:

$$D = N_0 - N \quad \text{then } N_0 = N + D \text{ where } N_0 \text{ is the original number of U atoms.}$$

$$\text{From the decay law: } \ln\left(\frac{N_0}{N_t}\right) = \lambda t \quad \text{then } \ln\left(\frac{N+D}{N}\right) = \lambda t$$

Number of U-238 atoms:

$$\text{Moles of U-238 in 1.0 g rock} = \frac{0.167}{238} \approx 7.0168 \times 10^{-4} \text{ moles}$$

1 mole of U-238 contains  $6.022 \times 10^{23}$  atoms

$$7.0168 \times 10^{-4} \text{ moles of U-238 contains} = 7.0168 \times 10^{-4} \times (6.022 \times 10^{23}) = 4.2255 \times 10^{20} \text{ atoms}$$

then  $N_t = N = 4.2255 \times 10^{20}$  atoms

$$\text{and } N_0 = 4.2255 \times 10^{20} + 2.4351 \times 10^{21} = 2.85765 \times 10^{21} \text{ atoms}$$

$$t_{1/2} = \frac{\ln 2}{\lambda} \quad \text{then } \lambda = \frac{\ln 2}{t_{1/2}} = \frac{\ln 2}{1.4 \times 10^{17}} = 4.951 \times 10^{-18} \text{ s}^{-1}$$

$$\ln\left(\frac{2.85765 \times 10^{21}}{4.2255 \times 10^{20}}\right) = 4.951 \times 10^{-18} t \quad t = 3.86 \times 10^{17} \text{ seconds}$$

**Assignment based items:**

1. Learners at a secondary school in Kampala visited a national museum as part of their study in **radioactivity and its applications**. During the visit, they interacted with scientists who were analyzing ancient wooden tools and studying radioactive substances used in laboratories.

At the museum laboratory, one scientist explained how **carbon dating** helps determine the age of historical objects. A small sample taken from a wooden artifact was tested and found to have a carbon-14 activity of **7.00 counts per minute per gram ( $\text{C min}^{-1} \text{g}^{-1}$ )**. The scientist further explained that freshly cut wood has a carbon-14 activity of **15.3 counts per minute per gram**, and the half-life of carbon-14 is **5570 years**.

**Task:** As a chemistry student, use the information provided in the scenario to determine the **age of the wooden artifact**.

2. At a secondary school in Uganda, a group of learners is carrying out a practical investigation in the science laboratory as part of their competency-based curriculum (CBC) studies. Their teacher has guided them to explore how radioactive substances decay over time, using bromine as an example. During the experiment, the learners carefully measure the rate of radioactive decay at regular time intervals using appropriate laboratory equipment.

After recording their observations, they notice that the rate of decay of the bromine sample has reduced by 25% after 96 minutes. The teacher then challenges the learners to apply their understanding of exponential decay and half-life concepts to interpret the results.

**Task:** As one of the learners in the group, use the information collected during the experiment to determine the half-life of bromine. Show clearly how you arrive at your answer.

**Ref: UACE 2017 Paper 1 Qn 1.**

3. In a senior four science class at a secondary school in Kampala, learners are carrying out a practical investigation on radioactive decay as part of their competency-based curriculum (CBC) activities. Their teacher presents them with a real-life inspired task involving a radioactive isotope used in medical research.

During the experiment, the learners are told that a sample of technetium  ${}^{100}_{43}\text{Tc}$ , which is a beta-emitting isotope, is being monitored in a controlled laboratory. The isotope has a half-life of 16 seconds, meaning that every 16 seconds, half of the radioactive material decays.

The learners observe that after 24 seconds, a total of 125g of the technetium sample has disintegrated. They are tasked with applying their understanding of half-life and exponential decay to determine the initial mass of the radioactive sample before the experiment began.

**Task:** As a chemistry learner, use the information provided to calculate the original mass of the technetium sample at the start of the experiment. Show all your working clearly and explain the steps you take to arrive at your answer.

4. At Uganda National Council for Science and Technology, a group of senior four learners are participating in a hands-on project about the safe use of radioactive materials in medicine. Their teacher explains that understanding how radioactive substances decay is important in areas such as cancer treatment and medical diagnosis.

During the activity, the learners are given a sample of a radioactive material similar to those used in hospitals. Using a radiation detector, they measure how the count rate (in counts per minute per gram) changes over time. The recorded data is shown below:

Count rate ( $\text{Cmin}^{-1}\text{g}^{-1}$ )	6400	5380	3810	2700	1910	1350
Time in minutes	0	1	3	5	7	9

The learners are tasked with analyzing this data to better understand the behavior of the material.

**Task:** As a chemistry student, help the senior four learners to plot a graph of count rate against time and use it to determine the half-life of the radioactive material followed by its decay constant.

Explain your steps clearly, showing how the graph helps you arrive at your answers.

5. At Kampala Secondary School, a group of Senior Four learners are participating in a science innovation project aimed at understanding how radioactive materials are used in agriculture and medicine. Their teacher introduces them to the element Gallium, which is useful in electronic devices and medical equipment, and also to a radioactive isotope of Protactinium used in nuclear research.

During the lesson, the learners discover that gallium exists naturally as a mixture of two isotopes with mass numbers 69 and 71. They are informed that the relative atomic mass of gallium is 69.8. Curious about the composition, the learners decide to determine the percentage abundance of each isotope.

Later, in the school laboratory, the teacher demonstrates the radioactive decay of protactinium-234. The learners carefully record the mass of the sample at different time intervals, obtaining the following data:

<b>Time (seconds)</b>	<b>20</b>	<b>40</b>	<b>60</b>	<b>80</b>	<b>100</b>	<b>120</b>
Mass of Pa-234 (g)	48.2	38.5	31.5	26.0	21.0	17.2

The learners are tasked with analyzing this data to better understand radioactive decay patterns, which are important in applications such as carbon dating, medical diagnostics, and environmental monitoring.

**Task:** As a chemistry student, use the information provided to;

(a) Determine the percentage abundance of the two isotopes of gallium with mass numbers 69 and 71.

(b) Plot a graph of  $\log_{10}(\text{mass})$  of protactinium-234 against time using the data provided.

(c) Determine with the aid of your graph in (b) the:

(i) initial mass of protactinium-234.

(ii) decay constant of protactinium-234.

(iii) half-life of protactinium-234.

6. A team of researchers at a nuclear laboratory in Uganda is studying radioactive materials to understand their behavior and safety implications. They are investigating different types of radiation and isotopes for potential applications in medicine and industry. Read the scenario carefully and answer the questions that follow.

**(a) Conceptual Understanding:** During their experiments, the researchers observed that some processes release energy by rearranging atoms, while others release energy by changing the nucleus itself. Similarly, they noticed that some particles emitted during radioactive decay carry different charges and masses.

**Task:** As a chemistry student, based on the researchers' observations, explain how a chemical reaction differs from a nuclear reaction and distinguish between an alpha particle and a beta particle.

**(b) Radioactive Decay:** One of the isotopes being studied is radium-229 ( $^{229}_{88}\text{Ra}$ ), which is known to decay by emitting alpha particles. The researchers recorded its half-life as 364 days.

**Task:** Considering the isotope's behavior:

(i) What do the researchers mean when they say radium-229 has a half-life of 364 days?

(ii) Starting from the decay law:  $2.303 \log \frac{A_0}{A_t} = \lambda t$

where  $A_0$  is the initial activity and  $A_t$  is the activity after time  $t$ , derive an expression for the half-life.

(iii) If the researchers left a sample of radium-229 for 500 days, calculate the percentage of the original sample that would have decayed.

**(c) Experimental Data Analysis:** The team also studied two isotopes, W and X, by measuring their decay rates at various times. The results are summarized in the table below:

Time (hours)	0	10	20	30	50	70
Rate of isotope W (counts/sec)	136	100	70	50	30	20
Rate of isotope X (counts/sec)	200	160	134	110	76	60

**Task:** Using the data collected by the researchers:

- On the same set of axes, plot a graph of decay rate (counts/sec) versus time for both isotopes W and X.
- Determine the half-life of each isotope and hence calculate their decay constants.
- Which isotope is least stable? Explain your answer based on the data.

### Nuclear Stability (Stability of the Nucleus)

This is a measure of the extent to which the nucleus of an atom stays or remains without disintegrating / decaying / breaking down. Therefore, a stable nucleus does not undergo radioactive decay and has a strong tendency to resist splitting up or fusion despite the fact that it contains positively charged protons which strongly repel each other.

An unstable nucleus undergoes radioactive decay with emission of alpha, beta and gamma rays. The decay continues until a stable nucleus is formed.

#### Factors affecting nuclear stability include:

The two main factors that determine nuclear stability are the neutron to proton ratio and the total number of nucleons (mass number) in the nucleus.

Characteristics of a stable nucleus include:

- An even number of both protons and neutrons.
- The neutron to proton ratio is close to 1:1.

#### **1. The neutron/proton (n/p) ratio**

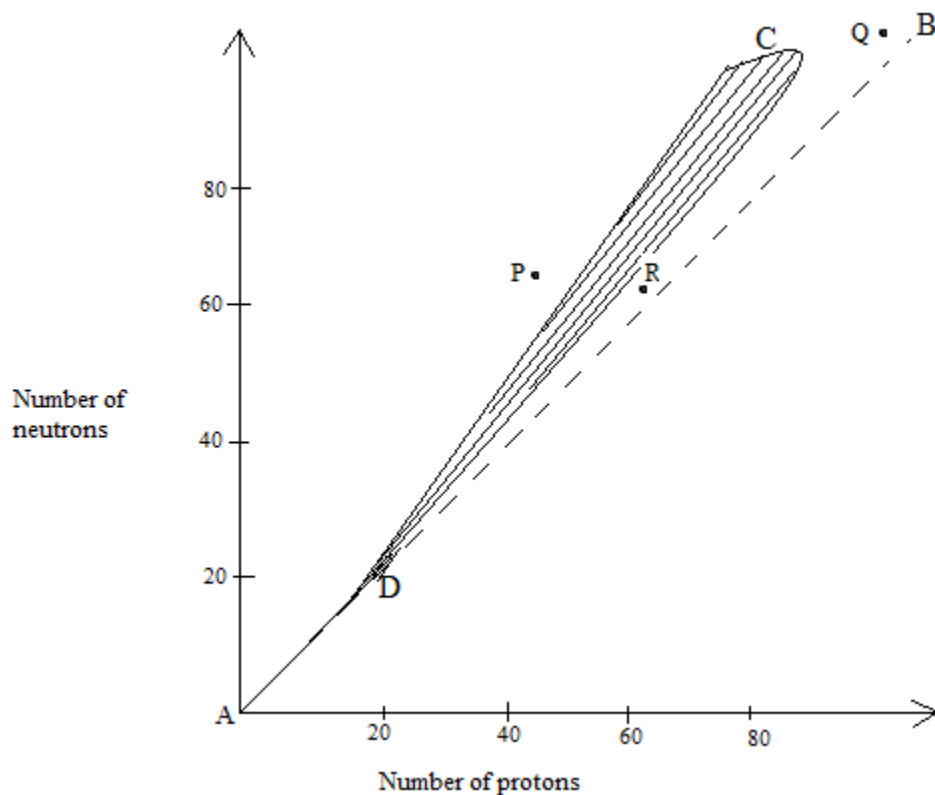
A stable nucleus always contains an **adequate number of neutrons** in order to **dilute the concentration of positive charge** due to **protons** which would **strongly repel** one another and cause **instability** hence nuclear fission. A nucleus will be stable if it maintains a balanced neutron to proton ratio of a specific range.

Too many neutrons or protons upset a balanced neutron to proton ratio disrupting the binding energy from the strong nuclear forces making the nucleus unstable and the atom becomes radioactive. This depends on the electrostatic repulsion between the excess protons and attraction between proton-neutron and neutron-neutron. Thus, nuclear stability is determined by the difference between the attraction and repulsion forces.

Therefore, stability of a nucleus is due to **stable arrangements of protons and neutrons in the nucleus**.

**The Band (or Belt) of Stability** (Stability Belt/band) is a graph of stable elements that shows a region of the neutron to proton ratio for which isotopes are stable.

It consists of a plot of number of neutrons against number of protons for naturally occurring stable nuclides or isotopes as shown below:



From the graph above, stable nuclei form a belt/band of stability i.e. **all stable nuclei** are located in the **stability belt or band** which has the following features;

- (a) Stable nuclei of isotopes with atomic number (proton number) less than or equal to 20 have a neutron to proton ratio equal to 1. They lie on line AB which represents isotopes with an **equal neutrons and protons** number. Along line AD, the nucleus is stable and non-radioactive but along line DB the nucleus is unstable and radioactive although it contains an equal number neutrons and protons. e.g.  $^{12}_6\text{C}$  and  $^{16}_8\text{O}$  are stable.
- (b) Stable nuclei of isotopes with atomic number greater than 20 and less than 83 have a neutron to proton ratio ( $n/p$ ) greater than 1 but not exceeding 1.6:1 because they should contain **slightly more neutrons than protons** to become stable.

The reason for this difference in ratio is because of the repulsive force between protons. The **stronger** the repulsion force between the many protons close to each other, the **more** neutrons are needed to stabilize the nuclei.

Neutrons help to separate the protons from each other in a nucleus so that they do not feel a strong repulsion force from other.

This explains why the stability belt curves towards the axis for number of neutrons. Therefore, the straight-line AB does not indicate stability for nuclei with proton number greater than 20. Line or region DC represents variation in the number of neutrons and protons for non-radioactive isotopes but along line DB the nuclides are unstable and radioactive.

- (c) With the increasing ratio of neutrons to protons, the stability is impossible after point C. Therefore, the stability belt ends with proton number 83 and neutron number 125.

**Note that:** From the stability belt (graph) above it shows that nuclei of isotopes whose plot of number of neutrons against proton number that lie outside the stability belt are unstable hence they undergo decay to form stable nuclei as explained below:

**(a) Isotopes to the left of the belt e.g. at P.**

A nucleus at P is unstable because it contains too many neutrons than adequate compared to protons (has a very high  $n/p$  ratio greater than 1.6). Such a nucleus can gain stability through any of the following ways:

(i) **Beta particle decay (emission).** During beta decay, a neutron splits up to form a proton and one electron. i.e.  ${}^1_0n$  (neutron)  $\longrightarrow$   ${}^1_1H$  (proton) +  ${}_{-1}^0e$  (electron)

In this case, a neutron is converted into a proton with formation of an electron which is emitted as a beta particle. The proton is retained in the nucleus while the electron is released. This transformation reduces the number of neutrons but increases the number of protons hence bringing the daughter nucleus diagonally downwards from left to right towards the stability belt.

(ii) **Neutron Emission.** Nucleus at P can attain stability by losing neutrons to reduce the number of neutrons in it hence reducing the neutron to proton ratio such that the daughter nucleus formed is close to or within the stability belt.

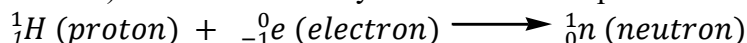
**(b) Isotopes to the right of the stability belt. e.g at R.**

Nuclei of such isotopes are unstable because they contain too many protons than adequate compared to neutrons i.e. they have a very low neutron to proton ratio. They attain stability by

(i) **Positron decay (Emission).** It involves conversion of a proton into a neutron and a positron.

A positron is a **positive beta particle**. The positron is demitted but the neutron is retained in the nucleus. This transformation increases the number of neutrons, thus moving the daughter nucleus diagonally upwards from right to left towards the stability belt.  ${}^1_1H \rightarrow {}^1_0n + {}^0_{+1}e$

(ii) **Electron capture.** In this case a nucleus captures an electron from the K-shell (energy level closest to the nucleus) which immediately combines with a proton in the nucleus to form a neutron. i.e.



This increases the neutron number but reduces the proton number hence increasing the neutron to proton ratio. This transformation continues until the daughter nucleus attains a stable n:p ratio.

(iii) **Proton Emission.** A nucleus can emit protons hence reducing their number in nucleus and increasing the neutron to proton ratio.

**(c) Isotopes above the stability belt. e.g. isotope at point Q.**

An isotope at Q has an atomic number greater than 83 and is too heavy, therefore it attains stability through alpha decay/emissions. This is because the emission of an alpha particle would cause the significant decrease in the mass of the isotope for stability to occur. It is very unstable and doesn't exist naturally because no nucleus has more protons than neutrons. e.g.  ${}^{234}_{90}Th \longrightarrow {}^{230}_{88}Ra + {}^4_2He$

Similarly, successive alpha decays and beta decays are possible especially in case of isotopes, which are very far from the belt of stability until they form a stable nucleus with atomic number less than 83. i.e. a series of alpha and beta decays occurs where the latter removes excess neutrons successively to form a nucleus with a neutron to proton ratio within the stability belt. Usually, such isotopes possess excess neutrons. They must therefore loose proportionally more neutrons than protons.

**Note that:** With all decay pathways, if the daughter nuclides are not on the stability belt, then subsequent decay pathways will occur until the daughter nuclei are on the belt of stability. This is known as the **decay series**.

## 2. Binding Energy of the Nucleus

This is the energy released or given out when a nucleus is formed from the individual protons and neutrons.

*Alternatively*, this is the energy required to separate a nucleus into individual protons and neutrons. The higher the binding energy of the nucleus, the harder it is to break the nucleus and the more stable the nucleus and the lower the binding energy, the less stable the nucleus is.

**Origin of binding energy:** Generally, the total mass of individual separate protons and neutrons is greater than the experimentally determined mass of the nucleus formed after their combination. i.e. formation of a nucleus from the individual protons and neutrons is accompanied by a decrease/loss in mass called **mass defect** (deficit).

This mass defect is converted into the binding energy of the nucleus according to Einstein's law  $E = mc^2$

where  $E =$  energy (binding energy),  $m =$  mass (mass defect)

$c =$  speed of light =  $3 \times 10^8$  m/s

By definition; **mass defect** is the difference between the actual mass of the nucleus and the total mass of the individual separate protons and neutrons.

When neutrons and protons combine to form a nucleus, there is a loss in mass called the mass defect which is converted into energy according to Einstein's law;  $E = mc^2$ . This energy overcomes (counteracts) the repulsion between the protons hence making the nucleus stable. This lost or released energy during nuclear formation is called the **binding energy**.

### 3. Atomic number/atomic mass

Stability reduces as atomic mass increases. Atoms with atomic number greater than 83 are too heavy to be stable.

Very light nuclei (with atomic number less than 20) are stable.

### 4. Half-life

The shorter the half-life the faster the radioactive nuclide decays and the less stable it is. The reverse is true.

### 5. Magic numbers

These are natural occurrences of specific neutron or proton numbers in isotopes that are particularly stable.

Nuclides with magic numbers 2, 8, 20, 28, 50, 82 and 114 as the number of protons or 2, 8, 20, 28, 50, 82, 126 and 184 as number of neutrons are stable.

These numbers of protons and neutrons are called **magic numbers** and are thought to represent closed nuclear shells comparable to closed electron shells for noble gases. Stable isotopes with these magic numbers of protons and neutrons include:  ${}^4_2\text{He}$ ,  ${}^{16}_8\text{O}$  and  ${}^{208}_{82}\text{Pb}$ .

#### **Item:**

At Uganda Industrial Research Institute, a team of young laboratory technicians is studying different atomic samples to determine why some nuclei are stable while others undergo radioactive decay. During the investigation, learners are provided with data showing the number of protons and neutrons for various atoms and are asked to analyze patterns of nuclear stability.

One learner observes that some atoms of the same element behave differently even though they share the same number of protons. The supervising scientist asks the group to explain this observation and further investigate factors affecting nuclear stability.

**Task:** As a chemistry learner, use the data provided and your knowledge of atomic structure, to respond to the following:

(a) Explain what is meant by the term *isotopes*.

(b) Apart from the neutron-to-proton ratio, analyse other factor(s) that influence the stability of isotopes.

(c) On a clearly labeled graph, plot the number of neutrons (y-axis) against the number of protons (x-axis) and:

(i) Draw the line representing neutron-to-proton ratio ( $n/p$ ) = 1.

(ii) Indicate the region where stable isotopes are found.

(iii) Show three points representing isotopes in the unstable region.

(d) The isotopes represented by the three unstable points in (c) above tend to undergo radioactive decay. Briefly analyse how each of these isotopes can achieve stability.

### Uses or Applications of Radioisotopes

**1. Carbon-14 dating (Radio dating):** Radioactive isotopes can be used to get good estimates of the ages of ancient materials especially carbon-14 isotope.

Carbon-14 is continuously formed in the upper atmosphere by effect of cosmic ray neutrons on nitrogen-14 atom. It is then rapidly oxidised in air to carbondioxide gas that enters the global carbon cycle.

The carbon-14 from carbondioxide is taken up or assimilated by plants during photosynthesis and by animals during respiration. There is negligible disintegration of this carbon-14 during the life time of plants and animals. However, when living organisms die, there is no more carbon-14 taken in. The carbon-14 starts to decay as its proportion in dead tissue falls with time and is proportional to the number of active atoms remaining (This is known as activity).

Carbon-14 dating is the best-known technique in which radioactive carbon-14 is used to date old dead (archeological samples of plant and animal materials). This is done by measuring the amount (concentration or

activity) of carbon-14 in the archeological (ancient) object. The amount of carbon-14 in a similar object of the same species which is a freshly killed sample is also measured. Since the half-life of carbon-14 is known (5570 years) then these values can be used to calculate the approximate age of the archeological object using the equations below:

$$\lambda = \frac{\ln 2}{t_{1/2}} \quad \text{or} \quad \lambda = \frac{0.693}{t_{1/2}} \quad \text{and} \quad \ln\left(\frac{N_o}{N_t}\right) = \lambda t \quad \text{or} \quad 2.303 \log\left(\frac{N_o}{N_t}\right) = \lambda t$$

where  $\lambda$  = decay constant of carbon-14

$t_{1/2}$  = half-life of carbon-14

$N_o$  = amount of carbon-14 in the fresh (live) sample or freshly killed.

$N_t$  = amount of carbon-14 in the dead or fossil (archeological) sample

$t$  = approximate age of the archeological sample.

**2. Treatment of cancer:** (a) Cancerous tissue is destroyed or killed in preference to healthy tissues by exposure to gamma rays, emitted from radioisotope such as cobalt-60 or Radium.

(b) Radioactive phosphorus has been used in treatment of leukemia.

(c) Radioactive iodine is used in treatment of goiter.

**3. Sterilizing surgical instruments and contaminated hospital blankets.** Gamma rays emitted by radioisotopes are used to kill bacteria and viruses on surgical instruments and contaminated hospital blankets.

**4. Tracer studies:** Radioactive isotopes are used as tracers for diagnostic purposes as well as in research on metabolic processes.

A radioactive tracer or label is a chemical compound in which one or more atoms in a strategic position in that compound have been replaced by another atom of the same element which is radioactive (radioisotope).

An object with a very small amount of a radioisotope attached to it/incorporated in it can readily be detected by picking up radiations from it by virtue of its radioactive decay, after a series of nuclear reactions. Thus, tracer studies use radioisotopes to track the path of a radioactive element through the body of an animal or plant and in chemical reactions. e.g.

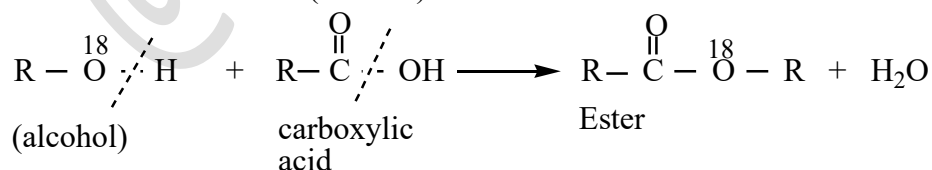
(a) Radioactive iodine-131 isotope has been used in both the diagnosis and treatment of thyroid disease and in research on the functioning of the thyroid gland and kidneys.

(b) The uptake of phosphorus by a plant can be traced using a phosphate fertilizer containing radioactive phosphorus-32 isotope.

(c) The introduction of radioactive iron-59 in the blood stream has enabled scientists to identify the role played by iron in blood formation.

(d) Study of reaction mechanism; when radioactive oxygen-18 isotope can be used to determine the mechanism of the reaction between a monocarboxylic acid and a primary alcohol as explained below;

A primary alcohol containing oxygen-18 isotope is reacted with a monocarboxylic acid. A mass spectrometer is used then to analyse the ester and water formed. The oxygen-18 isotope is found in the ester only and not in the water. This implies that the carbon to oxygen single bond in the carboxylic acid and the oxygen to hydrogen bond in the alcohol are broken (cleaved).



The dotted lines show the bonds that are broken (cleaved) during the reaction.

In this reaction, a non-radioactive oxygen atom in the alcohol is replaced by the radioactive oxygen-18. Due of its radioactivity, oxygen-18 undergoes a series of nuclear reactions during the esterification reaction. The path followed by oxygen-18 during the reaction with the carboxylic acid (also acid chloride or acid anhydride) is then traced from its original position in the reactants to the final position in the products.

**5. Food preservation:** Food stuffs are radiated with gamma rays emitted by radioisotopes which kill bacteria that are in food, hence preventing food spoilage.

**6. Detects leaks in buried (underground) water, oil or gas pipelines.** This is done by introducing a Gamma emitting radioisotope e.g. Cobalt-60 into the flow of water, oil or gas in the pipeline. The level of surface radioactivity is monitored using a detector and where a sudden increase in the radioactivity is detected is the point where the leakage is.

**7. Detection of wear in an engine.**

Radioactive materials help engineers find out how fast engine parts wear out.

- A small amount of a **radioactive isotope (tracer)** is added to engine parts such as piston rings or bearings.
- As the engine runs, tiny worn-off particles mix with the engine oil.
- The oil is then tested using a detector like a **Geiger–Müller tube**.
- If radioactivity in the oil increases, it shows that more material is being worn away.

**Why this is useful:**

- Helps detect wear early before serious damage occurs.
- Reduces maintenance costs.
- Improves engine lifespan and safety.

**8. Detection of metal fatigue.**

Metal fatigue occurs when a metal weakens after repeated use or stress.

- A radioactive tracer is placed inside or on the surface of the metal.
- As cracks begin to form, the radiation pattern changes.
- Special detectors pick up these changes and show where the metal is weakening.

Another method:

- Radiation is passed through the metal.
- If there are cracks or weaknesses, more radiation passes through those areas and is detected.

**Importance:**

- Used in aircraft, bridges, and machinery.
- Prevents accidents by detecting faults early.
- Ensures structural safety.

**9. Measurement and control of thickness of material (e.g. paper, metal, plastic).**

Radioactivity is widely used in industries to ensure materials have the correct thickness.

- A radioactive source is placed on one side of the material.
- A detector is placed on the opposite side.
- As radiation passes through:
  - **Thicker material** → absorbs more radiation → less reaches detector
  - **Thinner material** → absorbs less radiation → more reaches detector
- The detector sends signals to a control system that adjusts the machine automatically.

**Applications:**

- Paper mills.
- Metal sheet production.
- Plastic manufacturing.

**Advantages:**

- High accuracy.
- Continuous monitoring during production.
- Reduces waste and improves quality.

**10. Detection of the level of contents in a container.**

Radioactivity can be used to measure how full a container is, even if it is sealed.

- A radioactive source is placed on one side of the container.
- A detector is placed on the opposite side.

- When the container is:
  - **Empty** → **more radiation reaches detector.**
  - **Full** → **less radiation reaches detector (absorbed by contents).**
- The detected radiation level indicates how much material is inside.

**Used for:**

- Liquids (water, oil, chemicals).
- Solids (grains, powders).

**Benefits:**

- Works without opening the container.
- Suitable for dangerous or hot materials.
- Used in industries like oil refining, food processing, and chemical plants.

**Sample items about real life applications of atomic number, atomic mass, and isotopes:**

**1. Carbon Dating (Isotopes).**

**Item:** You work as an archaeologist and need to determine the age of an ancient fossil. You decide to use **carbon dating**, which relies on the isotope **carbon-14** to estimate how long it has been since the fossilized organism died.

**Task:** Why is carbon-14 used in carbon dating, and how does its properties help in dating ancient artifacts?

**Response:** Carbon-14 (a radioactive isotope of carbon) is used because living organisms continually absorb carbon, including carbon-14, from the environment. When they die, they stop absorbing carbon, and the carbon-14 in their bodies begins to decay (breakdown) at a known rate (half-life of about 5730 years). By measuring how much carbon-14 remains in a sample, scientists can calculate how long it has been since the organism died, thus determining the age of the fossil.

**2. Medicine: Radioactive Isotopes in Imaging (Tracer Studies).**

**Item:** You are a radiologist using a medical imaging technique called **Positron Emission Tomography (PET)** to help diagnose a patient. The method involves using radioactive isotopes.

**Task:** How are isotopes used in PET scans, and what role does their atomic properties play in medical diagnosis?

**Response:** In PET scans, a patient is injected with a small amount of a radioactive isotope (like **fluorine-18**). The isotope emits positrons as it decays, which interact with electrons in the body, producing gamma rays. Detectors pick up these gamma rays, allowing doctors to create images of the body's internal processes, such as brain activity or cancer cell growth. The isotope's half-life and ability to emit radiation are crucial in allowing the scan to work effectively without harming the patient.

**3. Nuclear Energy (Isotopes and Atomic Mass).**

**Item:** As an energy engineer, you're working with nuclear reactors that use uranium isotopes for power generation.

**Task:** How do uranium isotopes, particularly uranium-235, play a role in nuclear power generation, and what is the importance of their atomic mass and atomic number?

**Response:** In nuclear reactors, uranium-235 (an isotope of uranium) is used as fuel because it is **fissile**, meaning it can undergo fission when struck by neutrons. When uranium-235 nuclei split, they release a significant amount of energy. The atomic number of uranium (92) determines its place on the periodic table and the number of protons in the nucleus, while the atomic mass affects its ability to undergo fission. The heavier isotopes like uranium-235 are more likely to absorb neutrons and break apart, making them effective for energy production in reactors.

**4. Using Atomic Mass in Cooking.**

**Item:** You are a chemist who helps design food products, and you are analyzing the **nutritional value** of a food sample. You need to measure the amounts of **micronutrients** like iron in the product, which is measured by its atomic mass.

**Task:** Why is the atomic mass of elements like iron important in nutrition, and how is it related to daily dietary recommendations?

**Response:** The atomic mass of elements like iron is important in determining their **molar quantities**, which are used to calculate the **daily recommended intake** of nutrients. For example, iron (atomic number 26) has an atomic mass of approximately 55.85 amu. In nutrition, we calculate the amount of iron in a product using its atomic mass to ensure that people get the right amounts for healthy blood cell production and overall bodily functions.

#### 5. Water Treatment (Isotopes).

**Item:** You work in a water treatment facility and need to trace the source of contamination in a water supply. You use **isotope tracers** to identify the contamination.

**Task:** How do isotopes help in water treatment, and what specific properties make them useful in tracing contamination?

**Response:** Isotopes, such as **oxygen-18** or **hydrogen-2 (deuterium)**, can act as tracers in water sources. These isotopes have distinct atomic masses and behave slightly differently from their more common counterparts (oxygen-16 or hydrogen-1), making them detectable in water samples. By analyzing the ratio of these isotopes in water samples, scientists can trace the origin of water, determine its source, and identify any contamination from specific pollutants or chemicals.

#### 6. Smoke Detectors (Americium-241 Isotope).

**Item:** You are installing a smoke detector in your home. You notice that the detector uses a radioactive element called **americium-241**.

**Task:** Why is americium-241 used in smoke detectors, and how does its atomic number and mass contribute to its effectiveness?

**Response:** Americium-241 (atomic number 95, atomic mass 241) is used in smoke detectors because it is a **radioactive isotope** that emits alpha particles. These particles ionize the air inside the detector, creating a small electrical current. When smoke particles enter the detector, they disrupt the ionization process, which triggers the alarm. The atomic properties of americium-241, such as its ability to emit alpha particles, make it effective for this purpose.

#### 7. Heavy Water in Nuclear Reactors.

**Item:** As part of a nuclear power plant, you're working with **heavy water** ( $D_2O$ ) as a moderator in a reactor to slow down neutrons.

**Task:** Why is heavy water used in nuclear reactors, and how do its isotopic properties differ from regular water?

**Response:** Heavy water contains **deuterium**, an isotope of hydrogen with one neutron, compared to the regular hydrogen (which has no neutrons). The additional neutron in deuterium helps slow down neutrons effectively without absorbing them as regular hydrogen does. This makes heavy water a good neutron moderator in reactors, helping maintain a controlled nuclear chain reaction. The atomic mass and isotopic difference between regular water and heavy water are key to this function.

These scenario items show how atomic number, atomic mass, and isotopes are vital in various aspects of our daily lives, from medicine to energy production. They emphasize the practical applications of atomic science beyond the classroom.

#### Other Items:

**1.** In a Senior Three science class at a secondary school in Rubaga-Kampala, students are carrying out a group discussion during their chemistry lesson. Their teacher has just introduced the structure of the atom and explains that the nucleus contains protons, which are all positively charged.

One student, Amina, looks puzzled and raises her hand. She says, "We have learned in physics that like charges repel each other. If all protons in the nucleus are positively charged, why don't they push each other apart and cause the nucleus to break up?"

The teacher smiles and asks the class to think deeper about forces within the atom. She divides the students into groups and asks them to discuss and come up with an explanation for why the nucleus remains stable despite the repulsion between protons.

**Task:**

As a learner, explain to Amina and your group members why protons are able to stay together in the nucleus without causing it to split apart.

**Answer:** A stable nucleus always contains an **adequate number** of **neutrons** in order to **dilute** the **concentration** and **effect** of **positive charge** due to **protons** which would **strongly repel** one another and make the nucleus unstable hence nuclear fission.

*Alternatively,* protons repel each other because they are positively charged. However, when protons and neutrons are extremely close together inside the nucleus, the strong nuclear force dominates (becomes much stronger than) the electrostatic repulsion. The nuclear force is a **very strong attractive force** that binds together particles (**protons and neutrons** collectively called nucleons) and effectively “glues” them into a stable nucleus.

The neutrons have no charge and they don't add to repulsion but do contribute to the strong force, helping hold the nucleus together.

**2.** At Kawanda Secondary School, the Senior Four learners visited a nearby research center, Uganda Atomic Energy Council, to learn about atomic structure and the applications of radioactivity in everyday life.

During the visit, a scientist showed them a model of an atom and explained that it is made up of tiny particles called electrons, protons, and neutrons. She also demonstrated how some elements, like radium, are unstable and undergo radioactive decay. The learners observed a sample of radium-229 undergoing alpha decay and discussed how scientists use radioactive substances in medicine, agriculture, and research.

Later, the students were given a task to analyze what they had learned from the visit.

**Task:** As a chemistry student, use the information, respond to the following:

**(a)** The scientist explained the structure of an atom using a model. Evaluate the meaning of the terms:

(i) Electron.

(ii) Proton.

(iii) Neutron.

(iv) Isotope.

**(b)** The learners observed that radium-229 undergoes alpha ( $\alpha$ ) decay with a half-life of 364 days.

(i) What is meant by the statement “half-life of 364 days”?

(ii) After the decay, determine the mass number and atomic number of the product formed.

(iii) Radium belongs to Group II of the periodic table. Suggest the group of the decay product.

(iv) Calculate the percentage of radium-229 that will have decayed after 500 days.

**(c)** During the discussion, the scientist highlighted different uses of radioactive substances.

Briefly explain the principles underlying the following applications:

(i) Use of radioactive isotopes as tracers.

(ii) Dating of dead organic matter using carbon-14.

(iii) Determination of the mechanism for esterification.

# Periodic Table of the Elements

1 1IA 1A																	18 VIII 8A
1 H Hydrogen 1.008	2 IIA 2A											13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.99	12 Mg Magnesium 24.305	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	9 VIII 8	10 VIII 8	11 IB 1B	12 IIB 2B	13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.065	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 83.799
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.414	49 In Indium 114.818	50 Sn Tin 118.711	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.294
55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71 Lanthanide Series	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [209]	85 At Astatine [210]	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103 Actinide Series	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [265]	109 Mt Meitnerium [276]	110 Ds Darmstadtium [281]	111 Rg Roentgenium [289]	112 Cn Copernicium [285]	113 Nh Nihonium [286]	114 Fl Flerovium [289]	115 Mc Moscovium [288]	116 Lv Livermorium [293]	117 Ts Tennessine [294]	118 Og Oganesson [294]
			57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.243	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.055	71 Lu Lutetium 174.967
			89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [260]

Alkali Metal	Alkaline Earth	Transition Metal	Basic Metal	Semimetal	Nonmetal	Halogen	Noble Gas	Lanthanide	Actinide
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