MBEYA UNIVERSITY OF SCIENCE AND TECHNOLOGY

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SEMESTER I

MODULE NAME:INTRODUCTION TO MECHANICS

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CONTACT HOURS:MONDAY THROUGH FRIDAY WORKING HOURS

ATOMIC THEORY AND RADIOACTIVITY

We are going to discuss

- **Atomic particles and their properties ,**
- **Isotopes,**
- **Radioactivity**
    - **Natural**
    - **Artificial**
- **And their uses**

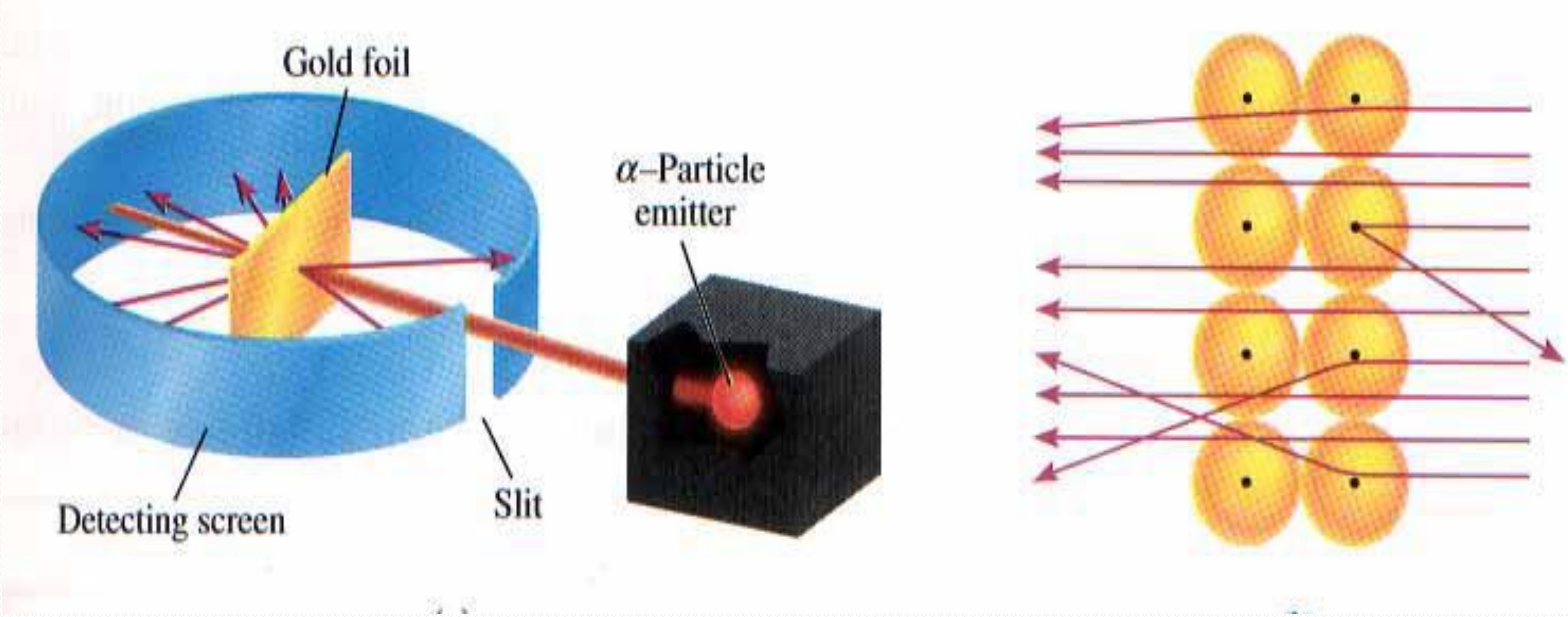
THE ATOM

- You have studied that all matter is made up of tiny particles called atoms.
- An atom is the smallest particle of matter that you can get by chemical means (although it is possible to split an atom using nuclear forces).
- Therefore an atom is the basic unit of matter from which all things are made.
- In this lesson we are going to study properties of various atoms and processes that take place in atoms.

THE CONSTITUENTS OF THE ATOM

RUTHERFORD'S SCATTERING EXPERIMENT

- Rutherford performed an experiment to determine the structure of the atom by using α–particles to disrupt the atom.



ATOMIC THEORY AND RADIOACTIVITY

A radioactive source substance was placed in an evacuated vessel, and emitted α–particles in a narrow beam on to a very thin metal foil of gold.

The path of the α–particles was found to be scattered by the gold atoms. Some of the α–particles were deflected through very large angles, as if they had reached a centre inside the gold atom which repelled them back.

From this observation Rutherford proposed that there was a concentration of positive charge inside the atom which repelled the positively charged α–particles.

From this he suggested the first correct structure of the atom (it is called Rutherford atomic model).

He suggested that,

i. The atom consists of a concentration of positive charge in a very tiny volume in the heart or centre of the atom, called the nucleus.
ii. The electrons move round the nucleus.
iii. Most of the atom is empty.

ATOMIC THEORY AND RADIOACTIVITY

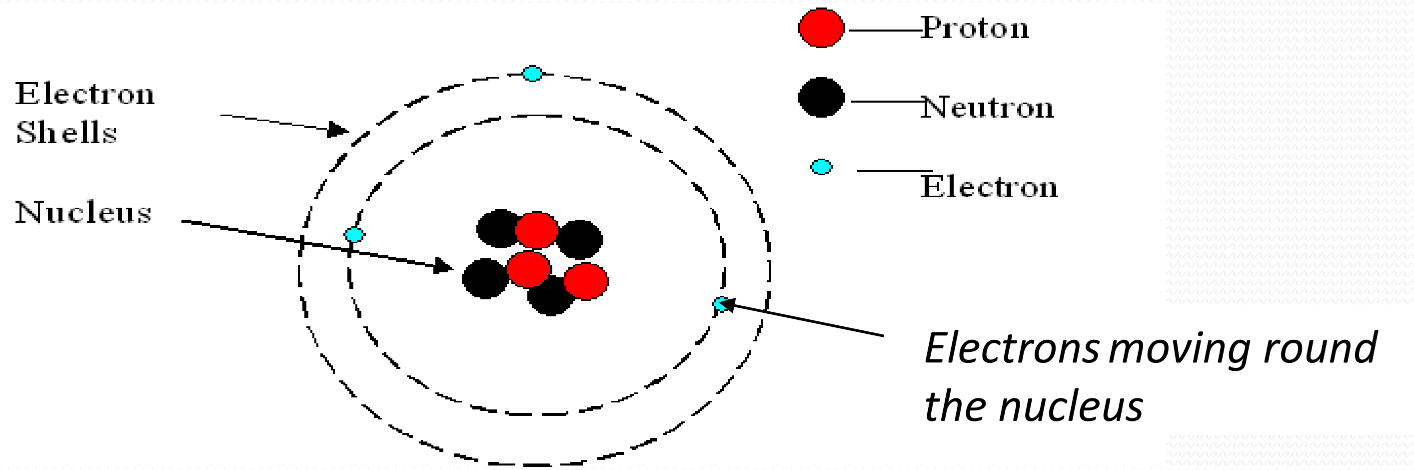
- Later, some experiments showed that the nucleus of the atom was built up of particles called protons and neutrons. Therefore the atom is made up of protons, neutrons and electrons.

- The proton has a positive charge and the electron has a negative charge which is equal in magnitude to that of the proton.

ATOMIC THEORY AND RADIOACTIVITY

- The proton is 1985 times as heavy as the electron; therefore the mass of the electron is negligible in comparison with protons and neutrons.
- The proton and the neutron have about the same mass.
- The mass of the atom is therefore concentrated in the nucleus.

ATOMIC THEORY AND RADIOACTIVITY



Rutherford atomic structure (model)

Table: Summary of properties of atomic particles

Particle	Charge	Mass
proton	+ve	1
neutron	Nil	1
electron	-ve	Nil

ATOMIC THEORY AND RADIOACTIVITY

MASS NUMBER

The sum of the number of protons and neutrons in a nucleus is called the MASS NUMBER. The mass number is usually represented by symbol A.

ATOMIC NUMBER

The number of protons in the atom is called the atomic number, presented by symbol Z. The atomic number also shows the number of positive charge. Therefore an atom of an element is represented by ${}_{Z}^{A}X$

where X is the chemical symbol of the element,

- A is the mass number and
- Z is the atomic number.

ATOMIC THEORY AND RADIOACTIVITY

To find the number of neutrons, subtract the atomic number from the mass number.

Number of neutrons = A-Z.

- **Note: Atomic number is a property of an element, i.e. each element has a unique atomic number and this characterizes what element it is.**
- For example the α–particle which has 2 protons and 2 neutrons has atomic number 2 and mass number 4 i.e. (2+2 = 4) hence symbol $^{4}_{2}\alpha$
- Oxygen $^{16}_{8}O$, Nitrogen $^{14}_{7}N$,etc.

ISOTOPES

- Isotopes are **atoms** of the same element with the same chemical properties but **different mass numbers**.
- The difference in mass numbers is due to the difference in number of neutrons.
- The chemical properties depend on the number of electrons round the nucleus or the number of protons only.

ATOMIC THEORY AND RADIOACTIVITY

Examples of isotopes are:

- Neon $^{20}_{10}Ne$ and $^{22}_{10}Ne$
- Chlorine $^{35}_{17}Cl$ and $^{37}_{17}Cl$
- Hydrogen $^{1}_{1}H$, $^{2}_{1}H$(deuterium) $^{3}_{1}H$ (tritium)
- Carbon $^{12}_{6}C$, $^{13}_{6}C$and $^{14}_{6}C$,
- Uranium $^{234}_{92}U$ and $^{235}_{92}U$, $^{238}_{92}U$ etc

Note that the atomic number is unique for every element

NATURAL RADIOACTIVITY

- This phenomenon was discovered by Becquerel in 1896, he found that a crystal of a uranium salt blackened a photographic plate even in complete darkness.
- He concluded that there was some sort of rays coming off the uranium salt which were blackening the photographic plate.
- This phenomenon is called **natural radioactivity.**
- **Natural radioactivity** or **Radioactive decay** is the process in which an unstable **atomic nucleus spontaneously** loses energy by **emitting radiation** in the form of **particles or electromagnetic waves.**

NATURAL RADIOACTIVITY

- **Natural radioactivity** is caused by the disintegration or decay of large heavy, unstable, nuclei like Uranium, Radon etc into simpler nuclei of other elements.
- The process is said to be spontaneous because it is not influenced by any physical factors such as temperature, pressure, time, etc.
- A nucleus is unstable if it is too big. All atoms with $Z > 82$ or $A > 209$ are unstable are radioactive and disintegrate until a stable isotope is formed

NATURAL RADIOACTIVITY

Usually **three types** of emissions are given off during radioactivity:**-**

- Alpha α–particles
- Beta β–particles
- Gamma γ–rays

NATURAL RADIOACTIVITY

Alpha (α) Decay:

Alpha decay occurs when the nucleus spontaneously ejects an α particle.
An α particle has 2 protons and 2 neutrons, (similar to He nucleus).
So when an atom undergoes α - decay, its atomic number decreases by 2 and its atomic mass decreases by 4.
Some examples of α - decay are the following:
Plutonium 239 undergoes alpha decay into Uranium 235

$$^{239}_{94}Pu \rightarrow\, ^{235}_{92}U + \,^{4}_{2}\alpha$$

Uranium 238 undergoes alpha decay into Thorium234

$$^{238}_{92}U \rightarrow\, ^{234}_{90}Th + \,^{4}_{2}\alpha$$

Radium -222 undergoes alpha decay into Polonium 219

$$^{222}_{86}Rn \rightarrow\, ^{218}_{84}U + \,^{4}_{2}\alpha$$

NATURAL RADIOACTIVITY

Beta(ß) Decay:

- An excess of neutrons in an atom's nucleus will make it unstable, and a neutron is converted into a proton. This results into a high speed electron being ejected.
- During this process, a ß particle (high speed electron) is released.
- As a result of ß$^{-}$ decay, the atomic number of the atom increases by 1.
- For example Thorium234 decays through ß emission to form Protactinium -234.This also decays through ß emission to form Uranium-234

$$^{234}_{90}Th \rightarrow ^{234}_{91}Pa + ^{0}_{-1}\beta$$

Then $$^{234}_{91}Pa \rightarrow ^{234}_{92}U + ^{0}_{-1}\beta$$

NATURAL RADIOACTIVITY

Radium228 can undergo beta decay to form Actinium

$$^{228}_{88}Ra \rightarrow ^{228}_{89}Ac + ^{0}_{-1}\beta$$

Carbon 14 can undergo β decay to form the element nitrogen:

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

Usually α and β radioactive decay are accompanied by emission of gamma radiations

NATURAL RADIOACTIVITY

Gamma Decay:

- Gamma Radiation (g) involves the emission of high energy electromagnetic waves from an atom's nucleus. These are called Gamma (γ) rays.
- No particles are emitted during gamma radiation.
- Gamma rays have no charge or mass, so their emission doesn't change the chemical composition of the atom. Instead, it results in a loss of radiant energy. Gamma ray emission occurs because the nucleus is often unstable after . α and ß decay.

NATURAL RADIOACTIVITY

- There are cases where pure emission occurs without a .α and ß decay radioactive decay, and this is where an isotope exists in two forms (nuclear isomers). They have the same atomic and mass numbers, but have different nuclear-energy content. So gamma emission occurs when the isomer goes from a higher to a lower energy form.
- For example the isotope protactinium-234; it emits rays when undergoing transition to the lower-energy state.

NATURAL RADIOACTIVITY

PROPERTIES OF THE EMMISSIONS

α–particles

- They are slow and heavy therefore they have low penetrating power
- they can be stopped by thin paper.
- They are only very slightly deflected by both magnetic and electric fields.
- Have a charge of +2
- They ionize other atoms (including air) strongly because they have large charge
- Have mass number 4 hence similar to Helium nucleus. Therefore an α–particles is a helium nucleus.
- Can be completely stopped by a sheet of paper,

NATURAL RADIOACTIVITY

β–particles

- They have medium penetrating power, are not absorbed by thin paper, but absorbed by aluminum sheet or plastic
- Have a charge of -1, they are the same as an electron
- They are very light and actually they are electrons.
- They are deflected by magnetic field
- They ionize other atoms but not as strongly as α–particles
- Can be stopped by aluminum shielding

NATURAL RADIOACTIVITY

γ–rays

- They are not particles, they are high frequency electromagnetic waves
- Highly penetrating and can be stopped only by thick blocks of lead.
- They are not deflected by a magnetic field
- They do not ionize other atoms but may cause atoms to emit other particles which will then cause ionization
- can only be reduced by substantial obstacles, such as a very thick piece of lead

NATURAL RADIOACTIVITY

RANDOM NATURE OF RADIOACTIVE DECAY (DISINTEGRATION)

- Radioactive decay is said to be a random process since we cannot predict which atom will decay at any instant. Also is not affected by physical conditions like temperature and pressure.
- But on average the number of atoms which decay at any instant is proportional to the number of atoms present at that particular time.
- We present mathematically as

$$\text{The rate of decay } \frac{dN}{dt} \alpha N$$

NATURAL RADIOACTIVITY

Therefore $$\frac{dN}{dt} = -\lambda N \qquad (1)$$

where

$\frac{dN}{dt}$ is the rate of decay (disintegration)

λ is the constant of proportionality. It is called the decay (disintegration) constant.

N is the number of atoms present at that time

Rearranging equation (1) we get

$$\frac{dN}{N} = -\lambda dt$$

NATURAL RADIOACTIVITY

Integrating both sides we get

$$\int_{N_0}^{N} \frac{dN}{N} = -\int_0^t \lambda dt$$

Where N_0 is the initial number of atoms and N is the number at any time t

$\log_e N \big]_{N_0}^{N} = -\lambda t$. Where N_0 is the initial number of atoms (number of atoms at time t=0)

Therefore $\log_e N - \log_e N_o = -\lambda t$

$$\Rightarrow \log_e \frac{N}{N_o} = -\lambda t$$

Therefore the number of atoms N remaining at any instant of time t is give as

$\mathbf{N=N_0e^{-\lambda t}}$

NATURAL RADIOACTIVITY

Half life

- Half life, symbol , is the time required for the quantity of a radioactive element (radioisotope) to fall to half its original amount.
- That is to say, if the quantity now is 32 atoms, and half-life is 10 days, the quantity will be 16 atoms after 10 days, 8 atoms after 10 more days, 4 atoms after another 10 days, etc

NATURAL RADIOACTIVITY

For example, the radioactive element bismuth ($^{214}_{83}Bi$) can undergo **α**-decay to form the element thallium ($^{210}_{81}Th$) and this reaction has a half-life of 5 days. Therefore after 5 days half of the initial amount of $^{214}_{83}Bi$ will have decayed and half will be remaining.

Relationship between half life and the disintegration constant

- At time t equal to half life the number of atoms of the sample remaining

$$N = \frac{1}{2} N_0$$

NATURAL RADIOACTIVITY

Substituting in equation (2) above we get

$$\frac{1}{2}N_0 = N_0 e^{-\lambda\tau}$$

$$\Rightarrow \frac{1}{2} = e^{-\lambda\tau}$$

$$\Rightarrow \log_e 2 = \lambda\tau$$

$$\Rightarrow 0.693 = \lambda\tau$$

$$\text{Therefore } \lambda = \frac{0.693}{\tau} \qquad \text{---------------(4)}$$

NATURAL RADIOACTIVITY

If we substitute this equation in equation (1) we get

$$\frac{dN}{dt} = -\frac{0.693}{\tau} N \qquad \text{-------------5}$$

- If we substitute the value of λ in equation (2) we get the number of atoms N remaining at any time t as

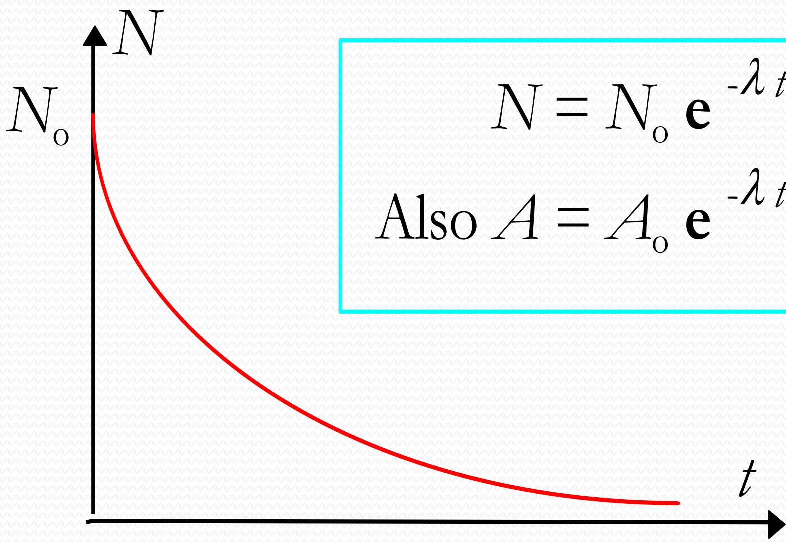
$$N = N_0 e^{-\frac{0.693}{\tau} t}$$

- It can also be shown that the rate of decay also follows the same pattern and hence the activity at any time t is given as $A = A_0 e^{-\lambda t}$

- Where A_o is the initial rate (rate at time t =0)

NATURAL RADIOACTIVITY

Variation of N as a function of time *t*



$$N = N_o\,\mathbf{e}^{-\lambda t}$$

$$\text{Also } A = A_o\,\mathbf{e}^{-\lambda t}$$

Number of radioactive nuclei decreases exponentially with time as indicated by the graph here.

Activity also varies in the same manner.

NATURAL RADIOACTIVITY

Assignment:

- Write seven(7) uses of radioactive substance and one dangerous of radioactive substance

ARTIFICIAL NUCLEAR REACTIONS

ARTIFICIAL NUCLEAR REACTIONS

- While many elements undergo radioactive decay naturally, nuclear reactions can also be stimulated artificially. There are 2 types of artificial nuclear reactions:

Fission

Nuclear fission is a process in which the nucleus of an atom splits into two or more smaller nuclei, and usually some by-product particles.

- Most commonly this is done by bombarding the nucleus of an atom with a neutron. The energy of the neutron causes the target nucleus to split into 2 parts.
- The most common fissile isotopes are uranium-235, (^{235}U), Plutonium-239 (^{239}Pu) and Thorium-232 (^{232}Th).

ARTIFICIAL NUCLEAR REACTIONS

- Uranium-235 and Plutonium-239 are the principal elements used in nuclear reactors and in nuclear bombs.
- The fissioning of ^{235}U can produce more than twenty different products.
- For example when uranium is bombarded by neutrons it produces smaller nuclei. In the process a number of neutrons are given off and may hit other uranium atoms

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{137}_{56}Ba + ^{84}_{36}Xe + 15\,^{1}_{0}n + \text{energy}$$

ARTIFICIAL NUCLEAR REACTIONS

- The neutrons that are released during a fission reaction can go on to stimulate fission reactions in other atoms creating a chain reaction.
- Similar processes can take place with Plutonium
- This process is the basis of the process of energy production in nuclear power plants and nuclear bombs.

ARTIFICIAL NUCLEAR REACTIONS

Fusion

- Nuclear fusion is the process by which multiple nuclei join together to form a heavier nucleus.
- In nuclear fusion usually two nuclei with low mass numbers combine to produce a single nucleus with a higher mass number.
- It is accompanied by the release or absorption of energy depending on the masses of the nuclei involved.
- Fusion of a deuterium nucleus with a tritium nucleus to form a helium nucleus and a free neutron with evolution of energy is an example of fusion reaction.

ARTIFICIAL NUCLEAR REACTIONS

$$^{2}_{1}H\ (Deuterium)\ +\ ^{3}_{1}H\ (tritium) \rightarrow\ ^{4}_{2}H\ (Helium) +\ ^{1}_{0}n\ + \text{Energy}$$

- Another simple fusion reaction is the fusion of a *neutron* and a *proton* to produce *deuterium* with evolution of energy.

$$^{1}_{0}n\ (neutron)\ +\ ^{1}_{1}p\ (proton) \rightarrow\ ^{2}_{1}H\ (Deuterium) + \text{Energy}$$

- Fusion could be the basis of the hydrogen bomb. Nuclear fusion of light elements releases the energy that causes hydrogen bombs to explode
- The sun and all stars, generate heat and light through nuclear fusion reactions.

ARTIFICIAL NUCLEAR REACTIONS

Energy in Nuclear Reactions

- The amount energy released in a nuclear fission or fusion is obtained using **Albert Einstein's** famous equation $E = mc^2$ which gives the relationship between energy and mass.
- Here E is the energy in a system, *m* is the mass converted into energy and *c* is the speed of light (*c* 3.0×10^8 m/s)
- The equation was developed by **Albert Einstein's** in 1905.

ARTIFICIAL NUCLEAR REACTIONS

Examples

- **In Fission**
- Nuclear power stations exploit this idea inside their reactors where uranium atoms are bombarded with neutrons, which cause the uranium to undergo nuclear fission.

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{236}_{92}U \rightarrow ^{138}_{55}Cs + ^{96}_{37}Rb + 2\,^{1}_{0}n + \text{Energy}$$

- If very precise measurements of all the particles before and after the process are done it is found that the total mass after the process is slightly smaller than before.
- The difference is called the **mass defect**.

ARTIFICIAL NUCLEAR REACTIONS

- The missing matter has been converted to energy and using Einstein's equation we can calculate how much energy has been released.

Element	Atomic Mass (kg)
${}^{235}_{92}U$	3.9014×10^{-25}
${}^{138}_{55}Cs$	2.2895×10^{-25}
${}^{96}_{37}Rb$	1.5925×10^{-25}
${}^{1}_{0}n$	1.6750×10^{-27}

ARTIFICIAL NUCLEAR REACTIONS

- We calculate the total mass before and after fission take place
- The total mass before fission (LHS of the equation) = **$3.9014 \times 10^{-25} + 1.6750 \times 10^{-27}$**

$= 3.91815 \times 10^{-25}$ kg

- The total mass after fission (RHS of the equation) = **$(2.2895 + 1.5925) \times 10^{-25} + 2(1.6750 \times 10^{-27})$**

$= 3.9155 \times 10^{-25}$ kg

Mass difference m = total mass before fission – total mass after fission

$= 3.91815 \times 10^{-25} – 3.91550 \times 10^{-25}$

$m = 2.65 \times 10^{-28}$ kg

ARTIFICIAL NUCLEAR REACTIONS

This reduction in mass results in the release of energy

$$E = mc^2$$

$$E = 2.65 \times 10^{-28} \times (3 \times 10^8)^2$$

$$\mathbf{E = 2.385 \times 10^{-11}\ J}$$

- This is produced from the fission of a single nucleus of uranium (1 atom).
- Large amounts of energy are released when a large number of nuclei undergo fission reactions.

ARTIFICIAL NUCLEAR REACTIONS

1 mole of atoms of uranium $6.022 \times 10^{23} \times 3.9014 \times 10^{-25}$kg = mass defect of $6.022 \times 10^{23} \times 2.65 \times 10^{-28}$ kg = 1.59583×10^{-4}kg will produce

$E = 1.59583 \times 10^{-4}\text{kg} \times (3 \times 10^{8})^{2} = 1.436247 \times 10^{13}$ Joules

This implies 1kg of ^{235}U will produce energy

$$E = \frac{1.436247 \times 10^{13}}{6.022 \times 10^{23} \times 3.9014 \times 10^{-25}}$$

$$= \mathbf{6.1132 \times 10^{13} J}$$

ARTIFICIAL NUCLEAR REACTIONS

In nuclear fusion

$$ {}_{1}^{2}H\ (Deuterium) + {}_{1}^{3}H\ (tritium) \rightarrow {}_{2}^{4}H\ (Helium) + {}_{0}^{1}n + \text{Energy} $$

Element	Atomic Mass (kg)
${}^{2}{}_{1}H$	3.345×10^{-27}
${}^{3}{}_{1}H$	5.008×10^{-27}
${}^{4}{}_{2}He$	6.647×10^{-27}
${}^{1}{}_{0}n$	1.6750×10^{-27}

ARTIFICIAL NUCLEAR REACTIONS

The total mass before fusion (LHS of the equation)

$= 3.345 \times 10^{-27} + 5.008 \times 10^{-27}$

$= \underline{8.353 \times 10^{-27}\ \text{kg}}$

The total mass after fusion (RHS of the equation)

$= 6.647 \times 10^{-27} + 1.675 \times 10^{-27}$

$= \underline{8.322 \times 10^{-27}\ \text{kg}}$

m = total mass before fission – total mass after fission

$m = 8.353 \times 10^{-27} - 8.322 \times 10^{-27}$

$m = 3.1 \times 10^{-29}$ kg

ARTIFICIAL NUCLEAR REACTIONS

$$E = mc^2$$

$$E = 3.1 \times 10^{-29} \times (3 \times 10^8)^2$$

$$\mathbf{E = 2.79 \times 10^{-12}\ J}$$

The energy released per fusion is 2.79×10^{-12}J

- Nuclear reactors are used at nuclear power plants for electricity generation and in propulsion of ships or production of artificial elements or useful radiations
- Heat from nuclear fission or fusion is passed to a working fluid (water or gas), which runs through steam turbines. These either turn electrical generators or drive a ship's propellers.
- All commercial power reactors are based on nuclear fission. They generally use uranium and its product plutonium as nuclear fuel.

END

Thanks For listening