TOPIC 1 Mass Defect and Binding Energy

SQ 19.1.1 What did Rutherford's experiments indicate?

Answer
Ernest Rutherford's experiments in 1911 indicated the existence of a dense, positively charged central part of the atom, the nucleus, of very small size surrounded by electrons.

SQ 19.1.2 What did Rutherford suggest in 1920?

Answer
In 1920 Rutherford suggested that the positive charge inside the nucleus is due to protons, and also predicted the presence of another particle having no charge. The prediction came true when the neutron was discovered in 1932.

SQ 19.1.3 What is nuclear physics?

Definition
Nuclear physics is the study of various aspects of atomic nuclei and sub-atomic particles.

SQ 19.1.4 What does the symbol $^A{}_{(Z)}X$ represent?

Answer
It represents a nuclide, where X is the chemical symbol of the element, Z is the atomic or charge number indicating the number of protons, and A is the mass number indicating the total number of nucleons.

SQ 19.1.5 Write the relation for the number of neutrons in a nucleus.

Formula
$N = A - Z$

SQ 19.1.6 Compare the radius of the nucleus with the radius of the atom.

Answer
The nucleus is very dense with a radius of the order of 10^{-14} m, surrounded by a cloud of electrons giving the atomic radius of the order of 10^{-10} m.

SQ 19.1.7 Define mass defect and write its formula.

Definition
The mass of a nucleus is always less than the total mass of all the protons and neutrons making up the nucleus. The lost or missing mass is called mass defect.

Formula
$\Delta m = [Zm_p + (A - Z)m_n] - m_{nucleus}$

SQ 19.1.8 What happens to the missing mass?

Answer
The missing mass is converted to energy, used in the formation of the nucleus.

Formula
$\Delta E = (\Delta m)c^2$

SQ 19.1.9 Define binding energy.

Definition
The energy required to break the nucleus into its constituents, that is neutrons and protons, is called binding energy.

SQ 19.1.10 Why is binding energy considered to have a negative value?

Answer
Binding energy is considered to have a negative value, similar to the absolute gravitational potential value which is taken as zero on the surface of the Earth.

SQ 19.1.11 Define binding energy per nucleon.

Definition
Binding energy per nucleon is a better measure of stability. It can be considered as the average energy needed to separate a nucleus into its individual nucleons.

SQ 19.1.12 Define the atomic mass unit and give its value.

Definition
The atomic mass unit is $\frac{1}{12}$ of the mass of an unbound neutral atom of carbon-12.

Value
$1\,\text{u} = 1.66 \times 10^{-27}\,\text{kg}$

SQ 19.1.13 What information does the binding energy per nucleon curve give?

Answer
The position of a nucleus on this curve gives information about the stability of the nucleus, and whether or not we can get energy from it by fission or by fusion.

SQ 19.1.14 What is the binding energy of the hydrogen nucleus?

Answer
The hydrogen nucleus has just one proton, so its binding energy is zero. The fall from hydrogen to helium is large, suggesting a large energy release when hydrogen is converted to helium.

SQ 19.1.15 Which is the most stable nuclide?

Answer
The curve reaches a maximum binding energy per nucleon of about 8.7 MeV for iron, which is the most stable nuclide. The region of most stable nuclei is between mass number 50 and 80.

SQ 19.1.16 For which nuclei is the binding energy per nucleon less?

Answer
Binding energy per nucleon is less for very light and very heavy nuclei. This is very significant, as it makes fusion and fission possible respectively.

SQ 19.1.17 When is energy obtained from a nuclear reaction?

Answer

Energy is obtained from any nuclear reaction in which the binding energy per nucleon of the products increases.

SQ 19.1.18 Find the mass defect of the helium nucleus.

Solution

$\Delta m = 2m_p + 2m_n - m_{nucleus} = 6.695104 \times 10^{-27} - 6.646786 \times 10^{-27}$

Result

$\Delta m = 0.048318 \times 10^{-27}\,\mathrm{kg}$

SQ 19.1.19 Find the binding energy of the helium nucleus.

Solution

$BE = \Delta mc^2 = 0.048318 \times 10^{-27} \times (3.0 \times 10^8)^2$

Result

$BE = 4.35 \times 10^{-12}\,\mathrm{J} = 27\,\mathrm{MeV}$

TOPIC 2 Nuclear Fission

SQ 19.2.1 Who discovered nuclear fission and how?

Answer

Otto Hahn and Fritz Strassmann of Germany observed that when slow moving neutrons are bombarded on uranium-235, barium and krypton are produced, along with about two or three neutrons.

SQ 19.2.2 In which two ways did the fission reaction differ from other nuclear reactions?

First

As a result of the breakage of the uranium nucleus, two nuclei of almost equal size are obtained, whereas in other reactions the mass difference between reactants and products was not large.

Second

A very large amount of energy is given out in this reaction.

SQ 19.2.3 Define a fission reaction.

Definition

A reaction in which a heavy nucleus splits up into two or more lighter nuclei of roughly equal size, along with the emission of energy, is called a fission reaction.

SQ 19.2.4 Write the fission reaction of uranium-235.

Reaction

${}^{235}_{92}\mathrm{U} + {}^{1}_{0}n \rightarrow {}^{141}_{56}\mathrm{Ba} + {}^{92}_{36}\mathrm{Kr} + 3{}^{1}_{0}n + Q$

SQ 19.2.5 How much energy is released in one fission of uranium?

Answer

By comparing the total energy on both sides of the equation, we find that in the fission of one uranium nucleus about $200\,\mathrm{MeV}$ of energy is given out.

SQ 19.2.6 What is conserved in a fission equation?

Answer

There is no difference between the sum of the mass numbers and the sum of the charge numbers on both sides of the equation.

SQ 19.2.7 Explain fission using the binding energy curve.

Explanation

The binding energy per nucleon for uranium is about $7.6\,\mathrm{MeV}$, while the products barium and krypton have about $8.5\,\mathrm{MeV}$ per nucleon.

Result

An energy of

$(8.5 - 7.6) = 0.9\,\mathrm{MeV}$

per nucleon is given out, so

$235 \times 0.9 = 211.5\,\mathrm{MeV}$

is released per uranium nucleus.

SQ 19.2.8 Does uranium fission always produce the same fragments?

Answer

No. The fission process of uranium does not always produce the same fragments. In fact, any two nuclei present in the upper horizontal part of the binding energy curve could be produced.

SQ 19.2.9 What is the nature of the fission products?

Answer

Several products may be produced in the uranium fission reaction, and all of these fission fragments are radioactive.

SQ 19.2.10 Which nuclides are mostly used for fission and why?

Answer

Fission is not confined to uranium alone; it is possible in many other heavy elements. However, fission takes place very easily with slow neutrons in uranium-235 and plutonium-239, so mostly these two are used.

SQ 19.2.11 Define a fission chain reaction.

Definition

During fission a uranium-235 nucleus absorbs a neutron and breaks into two nuclei, besides emitting two or three neutrons. By properly using these neutrons, fission can be produced in more atoms. This process is called a fission chain reaction.

SQ 19.2.12 What happens in an uncontrolled chain reaction?

Answer

The process proceeds rapidly and, in an infinitesimally small time, a large amount of energy along with a huge explosion is produced.

SQ 19.2.13 What condition keeps a chain reaction proceeding at a steady rate?

Condition

Only one neutron out of all those created in one fission reaction becomes the cause of further fission. The other neutrons either escape out or are absorbed in some other medium.

SQ 19.2.14 Why can a thin sheet of fissile material not sustain a chain reaction?

Reason

The resulting neutrons escape into the air, and so they cannot produce any fission chain reaction.

SQ 19.2.15 **What is required for a sustained chain reaction?**

Answer
A spherical lump of highly fissile heavy material, mostly uranium-235, is required. If the lump is sufficiently big, then most of the neutrons produced remain within it and cause further fission.

SQ 19.2.16 **How does fission energy compare with chemical reactions?**

Answer
The energy released in a nuclear fission reaction is much more than that of chemical reactions such as the burning of fossil fuels.

TOPIC 3 Nuclear Reactor

SQ 19.3.1 **What part does a reactor play in a nuclear power station?**

Answer
In a nuclear power station the reactor plays the same part as the furnace in a thermal power station. In a furnace coal or oil is burnt to produce heat, while in a reactor fission produces heat.

SQ 19.3.2 **In what form does the energy first appear in a reactor?**

Answer
The energy appears in the form of kinetic energy of the fission fragments. These fast moving fragments collide with one another and with uranium atoms, so their kinetic energy is transformed into heat energy.

SQ 19.3.3 **How is electricity finally produced in a nuclear power plant?**

Answer
The heat is used to produce steam, which in turn rotates a turbine. The turbine rotates the generator which produces electricity.

SQ 19.3.4 **Describe the core of a nuclear reactor.**

Description
The core is the most important and vital part of a reactor. Here the fuel is kept in the shape of cylindrical tubes.

SQ 19.3.5 **Which fuels are used in nuclear reactors?**

Answer
Uranium was used as fuel in first generation reactors, in which the quantity of uranium-235 is enriched from 2.4 to 3.0 percent, whereas in naturally occurring uranium it is only 0.7 percent.
Nowadays plutonium-239 and uranium-233 are also being used as fuel.

SQ 19.3.6 **What is the function of a moderator?**

Function
The function of a moderator is to slow down the speed of the neutrons produced during the fission process and to direct them towards the fuel.

Materials
Moderators are substances of small atomic weight, such as water or heavy water.

SQ 19.3.7 **Why are slow neutrons needed in a reactor?**

Reason
The neutrons produced in the fission reaction are very fast and energetic and are not suitable for producing fission in the reactor fuel. For this purpose slow neutrons are more useful.

SQ 19.3.8 **What is heavy water?**

Definition
Heavy water is made of deuterium, a heavy isotope of hydrogen, instead of ordinary hydrogen.

SQ 19.3.9 **What is the function of control rods?**

Function
Control rods arrange for the control of the number of neutrons, so that of all the neutrons produced in fission, only one produces further fission.

Material
They are made of cadmium or boron, because they have the property of absorbing fast neutrons.

SQ 19.3.10 **How are control rods used in an emergency?**

Answer
In case of emergency or for repair purposes, the control rods are allowed to fall back into the reactor, thus stopping the chain reaction and shutting down the reactor.

SQ 19.3.11 **Describe the heat exchanger of a reactor.**

Description
The temperature of the core rises to about 500 °C. This heat is transported to the heat exchanger with the help of water, heavy water or another liquid under high pressure.

Function
In the heat exchanger this heat is used to produce high temperature steam from ordinary water.

SQ 19.3.12 **How is nuclear waste disposed of?**

Answer
Radioactive waste is buried deep, many metres below the Earth's surface, where it can remain and decay without polluting the environment on the surface of the Earth.

TOPIC 4 Nuclear Fusion

SQ 19.4.1 **Define a fusion reaction.**

Definition
A nuclear reaction in which two light nuclei merge to form a heavy nucleus is called a fusion reaction.

SQ 19.4.2 **When is energy given out in fusion?**

Answer
The binding energy per nucleon increases up to
$A = 50$
Hence when two light nuclei merge to form a heavy nucleus whose mass number is less than 50, energy is given out.

SQ 19.4.3 What happens to mass during a fusion reaction?

Answer
During a fusion reaction some mass is lost and its equivalent energy is given out.

SQ 19.4.4 Why is fusion difficult to produce?

Reason
Two positively charged nuclei must be brought very close to one another. To do so, work has to be done against the electrostatic force of repulsion between them, so a very large amount of energy is required.

SQ 19.4.5 Compare the energy from fusion and fission.

Answer
In a fusion reaction more energy per nucleon can be obtained as compared to a fission reaction. However, in order to start the reaction a very large amount of energy has to be spent.

SQ 19.4.6 How much energy is released when deuterium and tritium fuse?

Answer
If deuterium and tritium are forced to fuse, then 17.6 MeV of energy is obtained.

SQ 19.4.7 What are fusion fuels?

Answer
Deuterium and tritium, which are forced to fuse to form helium, are termed fusion fuels.

SQ 19.4.8 What is the first method used to produce fusion?

Method
The two nuclei are accelerated towards one another at a very high speed. This method has been used in research study, but it cannot be used on a large scale.

SQ 19.4.9 What is a thermonuclear reaction?

Definition
The second method is based on the principle that the speed of atoms increases with temperature. The reaction that takes place at such extraordinarily high temperature is called a thermonuclear reaction.

SQ 19.4.10 What temperature is needed to start a fusion reaction?

Answer
To start a fusion reaction the temperature at which the required speed of the light nuclei can be obtained is about 15 million kelvin.

SQ 19.4.11 How has such a high temperature been achieved so far?

Answer
Ordinarily such a high temperature cannot be achieved. However, during the explosion of an atom bomb this temperature can be had for a very short time.

SQ 19.4.12 Why is fusion not yet used to produce electricity?

Reason
Until now the fusion reaction has been observed only in the experimental testing of the hydrogen bomb. A very large amount of energy can be achieved, but this reaction has not yet been brought under control like a fission reaction.

SQ 19.4.13 What is the artificial Sun project?

Answer
The artificial Sun is designed to mimic the real Sun. It is an experimental advanced superconducting Tokamak project in China which uses powerful magnetic fields to confine superheated plasma reaching temperatures over 100 million °C.

TOPIC 5 Activity and Half-Life

SQ 19.5.1 Why is radioactive decay called a random process?

Reason
The decay process is quite random and does not follow any regular pattern. We cannot foretell about any particular atom as to when it will decay; it could decay immediately or remain unchanged for thousands of years.

SQ 19.5.2 What does the fluctuation in decay curves show?

Answer
Fluctuation in decay curves is evidence of the random nature of radioactive decay.

SQ 19.5.3 What pattern is observed in a very large sample?

Answer
While we cannot predict when a single nucleus will decay, in a very large sample the decay follows a consistent pattern when we draw the number of radioactive nuclei against time.

SQ 19.5.4 What does the decay curve never touching zero mean?

Answer
The curve never touches zero, which means that the radioactivity never ends.

SQ 19.5.5 Define activity and write its unit.

Definition
The activity of a radioactive substance is the number of particles it emits per second. The number of such emissions per second is called the decay rate.

Unit
Its SI unit is the becquerel, where 1 Bq is one decay per second.

SQ 19.5.6 What is count rate?

Definition
The count rate of a nuclear radiation detector is the number of counts recorded per second. It is directly proportional to the activity.

SQ 19.5.7 **Define half-life.**

Definition

The time taken for the activity of a sample to decrease to half of any starting value is called half-life.

SQ 19.5.8 **Why can no radioactive element decay completely?**

Reason

In any half-life period only half of the nuclei decay, so an infinite time would be required for all the atoms to decay.

SQ 19.5.9 **On what does the number of atoms decaying in a period depend?**

Answer

The number of atoms decaying in a particular period is proportional to the number of atoms present at the beginning of the period.

SQ 19.5.10 **Write the radioactive decay equation.**

Formula

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

Here λ is the constant of proportionality called the decay constant.

SQ 19.5.11 **Define decay constant and write its unit.**

Definition

The decay constant of any element is equal to the fraction of the decaying atoms per unit time.

Unit

Its unit is s^{-1}.

SQ 19.5.12 **What does a large or small decay constant mean?**

Answer

If the decay constant of an element is large, then in a particular interval more of its atoms will decay. If the constant is small, then in that same interval fewer atoms will decay.

SQ 19.5.13 **Write the expression for absolute activity.**

Formula

$A = \lambda N$

Here the number of atoms N decreases with time.

SQ 19.5.14 **What is a decay curve?**

Definition

The graph drawn between the number of atoms present in a sample of a radioactive element and time is called a decay curve.

SQ 19.5.15 **How many atoms remain after n half-lives?**

Formula

$$N = \left(\frac{1}{2}\right)^n N_0$$

SQ 19.5.16 **After four half-lives, what fraction of a radioactive sample remains?**

Solution

$$N = \left(\frac{1}{2}\right)^4 N_0 = \frac{N_0}{16}$$

Result

Only 6.25% of the sample remains undecayed.

TOPIC 6 Radioactive Tracers

SQ 19.6.1 **What is a radioactive tracer?**

Definition

A radioactive isotope behaves in just the same way as the normal isotope inside a living organism, but its location and concentration can be determined easily by measuring the radiation it emits.

Use

Thus it acts as an indicator or tracer that makes it possible to follow the course of a chemical or biological process.

SQ 19.6.2 **What is the technique used with radioactive tracers?**

Technique

The technique is to substitute radioactive atoms for stable atoms of the same kind in a substance, and then to follow the tagged atoms with the help of a radiation detector.

SQ 19.6.3 **How are chemicals distributed in the human body?**

Answer

Some chemicals such as hydrogen and sodium present in water and food are distributed uniformly throughout the human body, while certain other chemicals are selectively absorbed by certain organs.

SQ 19.6.4 **How are radioisotopes produced?**

Answer

Radioisotopes of many elements can be made easily by bombardment with neutrons and other particles. As such isotopes are available and inexpensive, their use has expanded tremendously.

SQ 19.6.5 **How are radioisotopes used in chemistry and biology?**

Uses

Radioisotopes are used to find out what happens in many complex chemical reactions and how they proceed.
In biology they have helped in investigating the chemical reactions that take place in plants and animals.

SQ 19.6.6 **How are radioisotopes used in agriculture?**

Answer

By mixing a small amount of radioactive isotope with fertilizer, we can measure how much fertilizer is taken up by a plant using a radiation detector. From such measurements farmers can know the proper amount of fertilizer to use.

SQ 19.6.7 **How have radiation-induced mutations helped crops?**

Answer

Through the use of radiation-induced mutations, improved varieties of crops such as rice, chickpea, wheat and cotton have been developed. They have improved plant structure, more resistance to diseases and pests, and give better yield and grain quality.

SQ 19.6.8 Why must radiation treatment be carefully controlled?

Reason

Radiation treatment has to be carefully controlled to avoid damaging healthy tissues. Patients undergoing radiation treatment often feel ill as the radiation also damages some healthy tissues.

TOPIC 7 Annihilation Reactions

SQ 19.7.1 When does an annihilation reaction take place?

Definition

Annihilation is an event taking place whenever a particle and its antiparticle come close to each other.

SQ 19.7.2 Why are high energies required in elementary particle research?

Answer

In elementary particles research very high energies are required for investigations. Instead of collisions at their rest mass energies, the particles are accelerated to nearly the speed of light and then collided.

SQ 19.7.3 What is done at CERN's Large Hadron Collider?

Answer

At CERN's Large Hadron Collider, protons, antiprotons and other heavy nuclei are collided at nearly the speed of light, to create conditions similar to the early universe.

SQ 19.7.4 What insight do TeV-scale collisions offer?

Answer

Collisions of protons, antiprotons and other heavy particles at energies of the order of TeV offer insight into early universe conditions.

SQ 19.7.5 Which particles were predicted during such collisions?

Answer

During such collisions the electro-weak force mediation particles W^+ W^- and Z bosons were predicted, along with the top and bottom quarks, and most significantly the Higgs boson in July 2012.