

Topic 12.1 Structure and Properties of the Nucleus

The Two Particles

The atomic nucleus comprises two types of particles: protons and neutrons.

The Proton

A proton is the nucleus of the simplest atom, hydrogen, called protium. It has a positive charge of the same magnitude as that of the electron.

$$q = 1.6 \times 10^{-19} \text{ C}$$

$$m_p = 1.67 \times 10^{-27} \text{ kg}$$

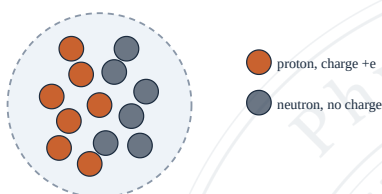
The Neutron

The neutron, whose existence was pointed out in 1932 by James Chadwick, is electrically neutral, and its mass is nearly the same as that of the proton.

Nucleons

The two types of particles in the nucleus, protons and neutrons, are together called nucleons.

Diagram



The nucleus holds Z protons and N neutrons, $A = Z + N$ nucleons

The nucleus holds Z protons and N neutrons, so that $A = Z + N$

Nuclides

Besides hydrogen, the nuclei of all other elements consist of both neutrons and protons. The different nuclei are called nuclides.

Atomic Number

The number of protons in a nucleus is called the atomic number, represented by Z .

Mass Number

The total number of nucleons, the sum of the neutrons and the protons, is represented by A and is called the atomic mass number, or simply the mass number.

$$A = Z + N$$

Here N represents the neutron number.

Notation

A given nuclide is written as ${}_Z^AX$, where X is the chemical symbol for the element.

Unified Mass Scale

To indicate the mass of atomic particles, the unified mass scale u is used instead of the kilogram. By definition $1 u$ is exactly one twelfth the mass of a carbon-12 atom.

$$1 u = 1.6606 \times 10^{-27} \text{ kg} = 931 \text{ MeV}$$

Masses on This Scale

$$m_p = 1.007276 u$$

$$m_n = 1.008665 u$$

$$m_e = 0.00055 u$$

Isotopes

Nuclei that contain the same number of protons but different numbers of neutrons are called isotopes.

Example

Carbon nuclei always have 6 protons but may have different numbers of neutrons. The isotopes ${}^{12}_6\text{C}$ and ${}^{13}_6\text{C}$ are stable, while ${}^{14}_6\text{C}$ is unstable and decays into nitrogen with the emission of a beta particle and a neutrino.

SHORT QUESTIONS

SQ 12.1.1 Define the atomic number and the mass number of a nuclide.

Atomic Number

The number of protons in the nucleus, written Z .

Mass Number

The total number of nucleons, written A

$$A = Z + N$$

Here N is the neutron number.

SQ 12.1.2 What is the unified mass unit, and what is it worth in kilogram and in MeV?

Definition

One unified mass unit is exactly one twelfth the mass of a carbon-12 atom.

Values

$$1 u = 1.6606 \times 10^{-27} \text{ kg}$$

$$1 u = 931 \text{ MeV}$$

SQ 12.1.3 Who discovered the neutron, and in which year?

James Chadwick

He pointed out the existence of the neutron in 1932. It is electrically neutral and has nearly the same mass as the proton.

SQ 12.1.4 Write the masses of the proton, the neutron and the electron on the unified mass scale.

Values

$$m_p = 1.007276 u$$

$$m_n = 1.008665 u$$

$$m_e = 0.00055 u$$

MCQ 12.1.1 The total number of nucleons in a nucleus is called the:

- | | |
|-------------------------|------------------------|
| A mass number | B atomic number |
| C neutron number | D charge number |

SOLUTION: It is the sum of the protons and the neutrons, $A = Z + N$.

MCQ 12.1.2 One unified mass unit is equal to:

- | | |
|------------------|------------------|
| A 511 keV | B 931 MeV |
| C 1 MeV | D 1.6 MeV |

SOLUTION: It is also $1.6606 \times 10^{-27} \text{ kg}$.

MCQ 12.1.3 Nuclei with the same number of protons but different numbers of neutrons are called:

- | | |
|-------------------|-------------------|
| A isobars | B isotones |
| C isotopes | D nucleons |

SOLUTION: Carbon-12, carbon-13 and carbon-14 are isotopes.

MCQ 12.1.4 The neutron was shown to exist in 1932 by:

- | | |
|----------------------------|--------------------------------|
| A Paul Dirac | B Carl Anderson |
| C Ernest Rutherford | D James Chadwick |

SOLUTION: It is electrically neutral and nearly as heavy as a proton.

MCQ 12.1.5 A nuclide has 87 nucleons and 50 neutrons. Its atomic number is:

- | | |
|-------------|--------------|
| A 37 | B 50 |
| C 87 | D 137 |

SOLUTION: $Z = A - N = 87 - 50$.

Topic 12.2 Fundamental Forces of Nature

LQ 7 starts here — Describe the four fundamental forces in nature.

The Four Forces

Despite the apparent complexity of the universe, all interactions in it are governed by four basic forces, known as the fundamental forces. They control how objects move, interact and behave, from nucleons in the atom to massive galaxies.

The List

Gravity, electromagnetism, the weak nuclear force and the strong nuclear force.

Gravitational Force

Gravity is the weakest of the four but it is a long-range force. It is an attractive force, proportional to the product of the two masses and inversely proportional to the square of the distance between them.

Where It Matters

For massive objects such as the Sun or the giant planets, gravity is significant. On the atomic level it is negligibly weak.

Electromagnetic Force

It is responsible for electric field and magnetic field interactions. Like gravity it follows an inverse square law, but it is much stronger. It governs atomic structure, chemical bonding, electricity, magnetism and the propagation of light.

Maxwell

James Clerk Maxwell formulated in 1861 a set of four fundamental equations which unified electricity and magnetism into electromagnetism, and showed that electric and magnetic fields are two aspects of a single electromagnetic force.

Why Another Force Is Needed

Electromagnetism holds matter together, but it does not explain how the nucleus is held together. With only electromagnetism and gravity the nucleus should fly apart, so a stronger force must exist inside it.

Strong Nuclear Force

Strong nuclear forces are the strongest attractive forces of the four. They hold the nuclei of atoms together and exist only inside the nucleus, so they are short-range forces.

Between Which Particles

The strong nuclear force acts as an attractive force between all nucleons. Protons attract each other by the strong nuclear force while at the same time repelling each other by the electric force, and a neutron, being neutral, attracts other neutrons or protons only through the strong force.

Weak Nuclear Force

Weak nuclear forces are responsible for radioactive decay, particularly beta decay, and for interactions involving neutrinos.

What Makes It Different

Unlike the other fundamental forces, the weak force can change the identity of particles, which makes it essential for nuclear fusion in stars and for the decay of unstable nuclei.

Strengths and Ranges

Force	Relative strength	Range
Gravity	10^{-38}	∞
Weak nuclear	10^{-13}	$< 10^{-18}$ m
Electromagnetic	10^{-2}	∞
Strong nuclear	1	$< 10^{-15}$ m

Strength and range of the four fundamental forces

LQ 7 ends here

SHORT QUESTIONS

SQ 12.2.1 Which of the four fundamental forces is the weakest, and which the strongest?

Weakest

Gravity, with a relative strength of about 10^{-38} .

Strongest

The strong nuclear force, taken as 1 on the same scale.

SQ 12.2.2 Compare the ranges of the four fundamental forces.

Infinite Range

Gravity and the electromagnetic force.

Short Range

The strong nuclear force acts over less than 10^{-15} m and the weak nuclear force over less than 10^{-18} m, so both act only inside the nucleus.

SQ 12.2.3 What is unusual about the weak nuclear force?

It Changes Identity

Unlike the other three forces it can change the identity of a particle, turning a neutron into a proton. That is what makes beta decay, and nuclear fusion in stars, possible.

SQ 12.2.4 What did Maxwell's equations show in 1861?

Unification

They showed that electricity and magnetism are not separate forces but two aspects of a single electromagnetic force, and they describe how electromagnetic waves propagate.

MCQ 12.2.1 The weakest of the four fundamental forces is:

- | | |
|----------------------------|--------------------|
| A the weak nuclear force | B electromagnetism |
| C the strong nuclear force | D gravity |

SOLUTION: Its relative strength is about 10^{-38} .

MCQ 12.2.2 The range of the strong nuclear force is about:

- | | |
|----------------|----------------|
| A 10^{-18} m | B 10^{-15} m |
| C infinite | D 10^{-10} m |

SOLUTION: That is why it acts only inside the nucleus.

MCQ 12.2.3 The force responsible for beta decay is the:

- | | |
|-----------------------------|-------------------------|
| A strong nuclear force | B electromagnetic force |
| C weak nuclear force | D gravitational force |

SOLUTION: It is the only force that can change the identity of a particle.

MCQ 12.2.4 Electricity and magnetism were unified into one force by:

- | | |
|------------------|------------|
| A Maxwell | B Faraday |
| C Dirac | D Einstein |

SOLUTION: His four equations date from 1861.

Topic 12.3 Matter and Anti-Matter

LQ 3 starts here — What is the difference between matter and anti-matter? Discuss the reasons why our universe is almost entirely composed of matter.

Dirac's Prediction

It was predicted by Paul Dirac in 1928 that the fundamental particles have their anti-particles.

What an Anti-Particle Is

The rest mass of an anti-particle is the same as that of the corresponding particle, but with opposite charge and magnetic moment.

The Positron

The positron is the anti-particle of the electron and is represented by e^+ . Its rest mass is the same as that of an electron but it carries a positive charge of the same magnitude.

The First One Found

The positron was the first anti-particle to be discovered, by Anderson in 1932 in a cloud chamber experiment. Many anti-particles have been discovered since.

Notation

Anti-particles are usually represented by a letter with a bar over it, so the anti-proton is $\bar{p}$ and the anti-neutrino is $\bar{\nu}$.

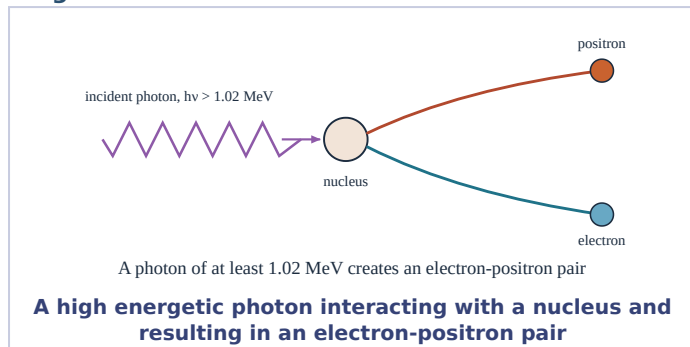
Elementary Particles

Quarks and leptons have been recognized as the fundamental, or elementary, particles among the very many discovered particles, and these too have their anti-particles.

Pair Production

Pair production occurs when a gamma ray, a high energy photon, passes near an atomic nucleus, and an electron-positron pair is emitted.

Diagram



Why a Nucleus Is Needed

The presence of a third particle, such as a nucleus, is necessary to conserve linear momentum.

Threshold Energy

By mass-energy equivalence the minimum energy of the photon must equal the sum of the rest mass energies of the created particles.

$$E = 2m_e c^2 = 1.02 \text{ MeV}$$

Below and Above Threshold

A photon with less than 1.02 MeV cannot produce a pair. A photon with more creates the pair, and the excess energy goes into the kinetic energies of the two particles.

What Is Conserved

Pair production satisfies the laws of conservation of charge, of momentum and of energy, and it can occur for any particle and anti-particle.

LQ 3 ends here

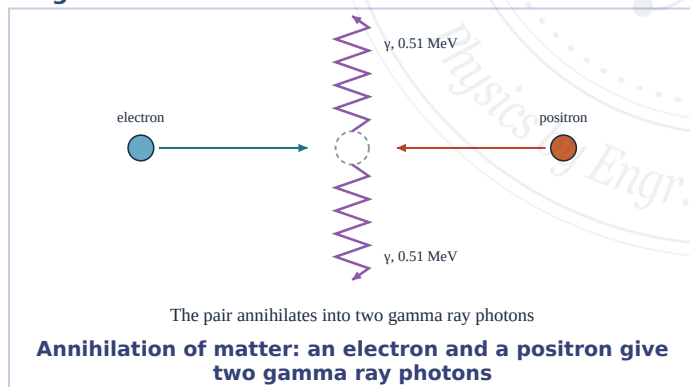
LQ 4 starts here — Explain the phenomenon of pair annihilation with an example. Explain the utility of its principle in the medical field.

Annihilation of Matter

This is the opposite process. When an electron and a positron interact they annihilate into two gamma ray photons.



Diagram



LQ 4 ends here

LQ 5 starts here — Explain the law of conservation of energy and momentum in electron-positron pair annihilation.

Energy of Each Photon

Each gamma ray photon carries the rest mass energy of an electron.

$$E = m_e c^2 = 0.51 \text{ MeV}$$

What Is Conserved

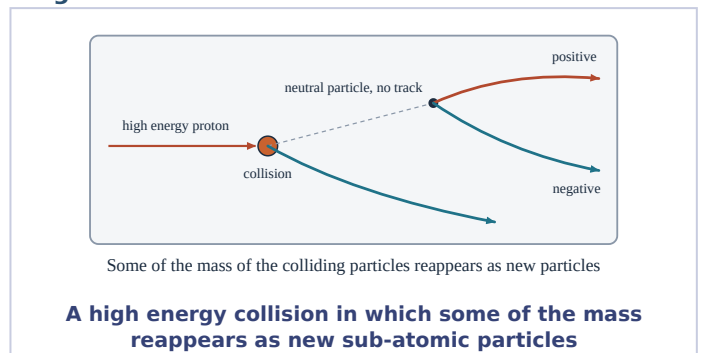
In an annihilation reaction energy and momentum are conserved. Other particle and anti-particle pairs annihilate in the same way — proton and anti-proton, lepton and anti-lepton, quark and anti-quark.

LQ 5 ends here

New Particles From a Collision

The Large Hadron Collider at CERN has revealed that some of the mass of colliding particles is changed into electromagnetic radiation according to Einstein's equation, and the left over mass appears in the form of new sub-atomic particles.

Diagram



SHORT QUESTIONS

SQ 12.3.1 What is an anti-particle?

Definition

A particle with the same rest mass as its partner but with the opposite charge and magnetic moment.

Example

The positron is the anti-particle of the electron, of equal mass but positive charge.

SQ 12.3.2 Why must a nucleus be present for pair production to occur?

Momentum

A third body is needed to take up recoil, so that linear momentum is conserved. The nucleus provides it, which is why pair production cannot happen in empty space.

SQ 12.3.3 A photon of 3 MeV produces an electron-positron pair. How much energy goes into the kinetic energies?

Working

$$E_{\text{threshold}} = 1.02 \text{ MeV}$$

$$K.E = 3 - 1.02 = 1.98 \text{ MeV}$$

The excess is shared as the kinetic energies of the two particles.

SQ 12.3.4 Who discovered the positron, and how?

Anderson

He discovered it in 1932 in a cloud chamber experiment. It was the first anti-particle to be found, and Dirac had predicted the existence of anti-particles in 1928.

SQ 12.3.5 Why are two photons of 0.51 MeV produced in electron-positron annihilation?

The Energy

Each photon carries the rest mass energy of one of the particles.

$$E = m_e c^2 = 0.51 \text{ MeV}$$

Why Two

A single photon could not conserve momentum, since the pair may be at rest before the annihilation.

MCQ 12.3.1 The existence of anti-particles was predicted in 1928 by:

A Carl Anderson

B **Paul Dirac**

C James Chadwick

D Murray Gell-Mann

SOLUTION: Anderson found the positron four years later.

MCQ 12.3.2 The minimum photon energy for pair production is:

A 0.51 MeV

B 2.04 MeV

C **931 MeV**

D 1.02 MeV

SOLUTION: It is twice the rest mass energy of an electron.

MCQ 12.3.3 Pair production cannot occur in empty space because it would violate the conservation of:

- A charge
B energy
C **momentum**
D baryon number

SOLUTION: A nucleus is needed to take up the recoil.

MCQ 12.3.4 Each photon produced in electron-positron annihilation carries:

- A 1.02 MeV
B **0.51 MeV**
C 931 MeV
D 0.25 MeV

SOLUTION: It is the rest mass energy of one of the two particles.

MCQ 12.3.5 An anti-particle differs from its particle in its:

- A rest mass
B spin magnitude
C speed
D **charge**

SOLUTION: The rest masses are the same.

Topic 12.4 Radioactivity

LQ 1 starts here — What is meant by radioactivity? Compare the properties and behaviour of the three types of radiation.

Natural Radioactivity

Nuclei whose atomic numbers are greater than 82 are found naturally unstable, and these nuclei spontaneously emit radiations. Such nuclei are called radioactive and the emission is known as natural radioactivity.

The Three Radiations

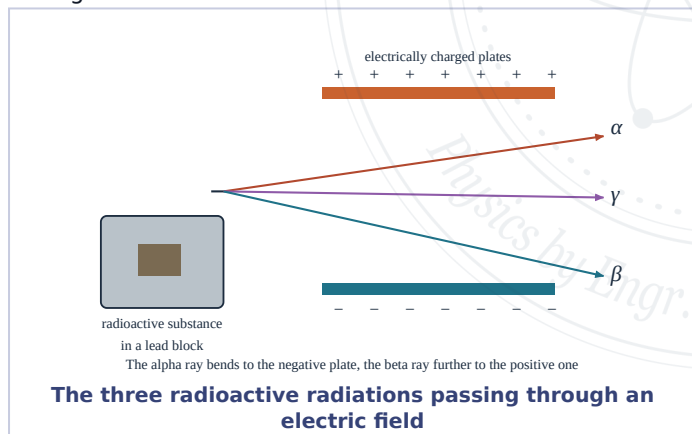
They are of three types: the α , β and γ radiations.

Artificial Radioactivity

Unstable isotopes can also be produced in the laboratory by bombarding a stable element with high energy particles such as neutrons, protons, alpha particles or gamma rays. This is called artificial radioactivity, and the isotopes are called radioisotopes or radionuclides.

In an Electric Field

The three radiations are deflected differently when passed through an electric field.



Alpha Particles

They deflect towards the negative terminal, showing that they carry a positive charge. They are emitted at high speeds, typically a few percent of the speed of light, but they travel only several centimetres in air because of their large mass.

Beta Particles

They deflect towards the positive terminal, showing that they carry a negative charge. Their deflection is greater than that of the alpha particles, which proves that they are lighter. They are fast-moving electrons and move with speeds up to 0.9995 of the speed of light.

Gamma Radiations

They pass through the field without deflection, showing that they have no charge. They are electromagnetic radiations consisting of photons, moving with the speed of light, with the highest penetrating power but the lowest ionization power.

Comparison

Characteristics	α -particles	β -particles	γ -rays
Nature	helium nuclei, $2e$	electrons or positrons, $\pm e$	e.m. waves, no charge
Typical source	radon-222	strontium-94	cobalt-60
Ionization	about 10^4	about 10^2	about 1
Range in air	several centimetres	several metres	inverse square law
Absorbed by	a paper	1-5 mm of Al sheet	1-10 cm of lead sheet
Energy spectrum	same energy	variable energy	variable energy
Speed	$\sim 10^7$ m s $^{-1}$	$\sim 10^8$ m s $^{-1}$	3×10^8 m s $^{-1}$

The characteristics of alpha, beta and gamma radiations

LQ 1 ends here

LQ 2 starts here — Elaborate the phenomenon of beta-positive decay and beta-negative decay with examples.

Alpha Decay

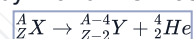
If the nucleus has more protons than neutrons, the electrostatic force of repulsion becomes greater than the strong nuclear force of attraction, the nucleus becomes unstable and it emits an alpha particle.

What an Alpha Particle Is

An alpha particle is a helium nucleus, made of two protons and two neutrons.

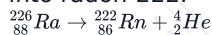
The Change

The nucleus loses two protons and two neutrons, so the atomic number falls by 2 and the mass number falls by 4.

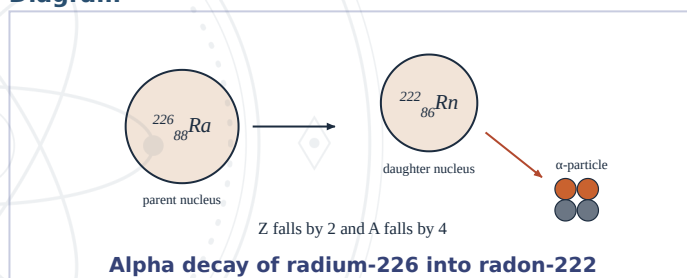


An Example

A radium-226 isotope emits an alpha particle and decays into radon-222.



Diagram



Transmutation

The daughter nucleus is a different element from the parent nucleus. This change of one element into another is called the transmutation of the elements.

Disintegration Energy

The mass of the parent nucleus is greater than the total mass of the daughter nucleus and the alpha particle, so the total mass-energy of the decay products is less than that of the original nuclide. This difference is called the disintegration energy, or the Q-value of the decay.

Beta Minus Decay

Some nuclides have a neutron to proton ratio that is too large. In this process a neutron in the nucleus decays into a proton and an electron, plus an anti-neutrino.



Not Orbital Electrons

The beta particles are not the orbital electrons; they are created within the nucleus at the moment of emission, although they are indistinguishable from orbital electrons.

The Neutrino

Both the neutrino and the anti-neutrino have zero charge and a very small mass, which is why they are very difficult to observe.

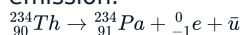
The General Decay

No nucleons are lost, so the mass number stays the same while the atomic number rises by one.



An Example

Thorium is unstable and decays into protactinium by beta emission.



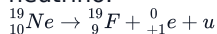
Beta Plus Decay

Other nuclides have a neutron to proton ratio that is too small for stability and decay by emitting a positron instead of an electron. A proton in the nucleus decays into a neutron and a positron, plus a neutrino.



An Example

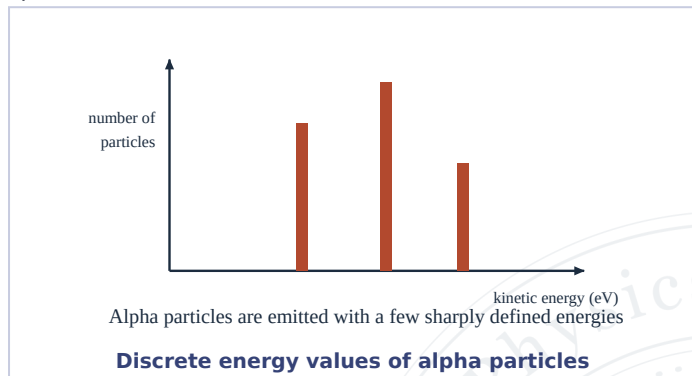
Neon decays into fluorine by emitting a positron and a neutrino.



LQ 2 ends here

Energy of the Alpha Particles

For a particular radionuclide every emitted alpha particle has the same sharply defined kinetic energy, so a plot of the number of particles against energy shows distinct spikes.

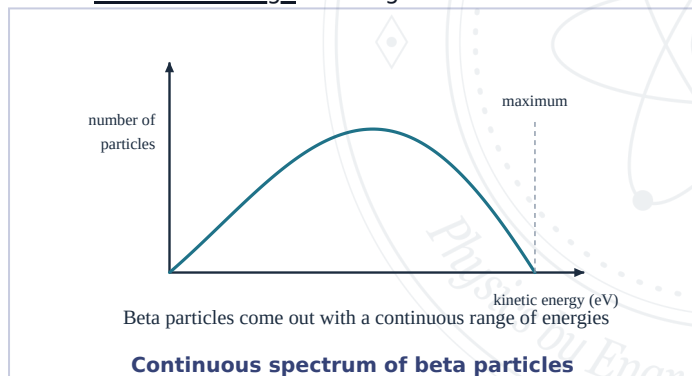


Energy of the Beta Particles

In beta emission the energy is shared between the beta particle and the anti-neutrino in varying proportions, although the sum is the same in every case.

The Spectrum

The energy of the electron or the positron may therefore range from zero up to a maximum value, so beta particles have a continuous range of energies.



What Still Holds

The principles of conservation of momentum and of energy apply in both alpha and beta emission.

Gamma Radiation

The emission of gamma radiation from a nucleus is represented by



Here the starred symbol represents an excited nucleus and the plain one the ground state of the nucleus.

SHORT QUESTIONS

SQ 12.4.1 Above which atomic number are nuclei found to be naturally unstable?

Above 82

Nuclei with Z greater than 82 are naturally unstable, and they spontaneously emit radiation. This is natural radioactivity.

SQ 12.4.2 What is artificial radioactivity?

Definition

Radioactivity produced in the laboratory by bombarding a stable element with high energy particles such as neutrons, protons, alpha particles or gamma rays, so that it becomes unstable and emits radiation.

The Products

The unstable isotopes so made are called radioisotopes, or radionuclides.

SQ 12.4.3 Why does an alpha particle travel only a few centimetres in air?

Reason

It is a heavy, doubly charged particle, so it ionizes the air very strongly, about 10^4 ion pairs per millimetre. It therefore loses its energy quickly and is stopped in a few centimetres.

SQ 12.4.4 What happens to Z and A in each of the three decays?

Alpha Decay

Z falls by 2 and A falls by 4.

Beta-Minus Decay

Z rises by 1 and A is unchanged.

Gamma Emission

Neither Z nor A changes; only the excited nucleus falls to its ground state.

SQ 12.4.5 What is meant by the transmutation of the elements?

Definition

The change of one element into another, which happens whenever the atomic number of the nucleus changes, as in alpha and beta decay.

SQ 12.4.6 What is the Q-value of a decay?

Definition

The disintegration energy. The mass of the parent nucleus exceeds the total mass of the products, and the mass-energy difference appears as the Q-value.

$$Q = \Delta mc^2$$

SQ 12.4.7 A nuclide ${}^{238}_{92}\text{U}$ emits an alpha particle. Write the daughter.

Working

$$A = 238 - 4 = 234$$

$$Z = 92 - 2 = 90$$



MCQ 12.4.1 Naturally radioactive nuclei have an atomic number greater than:

A 52

B 92

C 82

D 12

SOLUTION: Above that the nucleus is no longer stable.

MCQ 12.4.2 In alpha decay the mass number falls by:

A 4

B 2

C 1

D 0

SOLUTION: An alpha particle carries away two protons and two neutrons.

MCQ 12.4.3 In beta-minus decay the atomic number:

A falls by one

B is unchanged

C rises by one

D rises by two

SOLUTION: A neutron becomes a proton.

MCQ 12.4.4 Gamma emission changes:

A neither Z nor A

B Z only

C A only

D both Z and A

SOLUTION: The excited nucleus simply falls to its ground state.

MCQ 12.4.5 The radiation with the greatest ionizing power is the:

A beta particle

B gamma ray

C neutrino

D alpha particle

SOLUTION: It gives about 10^4 ion pairs per millimetre in air.

MCQ 12.4.6 A sheet of paper is enough to absorb:

A beta particles

B alpha particles

C gamma rays

D all three

SOLUTION: Beta particles need aluminium and gamma rays need lead.

MCQ 12.4.7 The nuclide ${}^{234}_{90}\text{Th}$ decays by beta emission into:

- A ${}^{230}_{88}\text{Ra}$ B ${}^{234}_{89}\text{Ac}$
C ${}^{238}_{92}\text{U}$ D ${}^{234}_{91}\text{Pa}$

SOLUTION: The mass number is unchanged and Z rises by one.

Topic 12.5 Fundamental Particles

LQ 8 starts here — Describe the classification of elementary particles.

Definition

By a fundamental particle we mean a particle that has no internal structure, which means that it is indivisible.

What They Are

At present the fundamental constituents of matter are considered to be quarks, of which protons, neutrons and mesons are made, and leptons, which include electrons, positrons and neutrinos.

New Particles

When a nucleus is smashed in an ultra high energy particle accelerator, or two high energy particles collide, entirely new types of particles are created which do not exist within the atoms of ordinary matter. More than a hundred have been identified and classified into families.

Strange Particles

The particles the theoretical scheme did not account for were named strange particles. They are always created in pairs: when a pion collides with a proton, the two strange particles kaon and lambda are created.



Spin

All particles spin on their axes, and the spin of a charged particle makes it a tiny magnet. The characteristic spin of the electron, the proton and the neutron is $1/2$, that of the photon is 1 and that of the pion is taken as zero.

Fermions

Half-spin particles obey Pauli's exclusion principle, which says that only one particle of a kind occupies a given quantum state. These are called fermions.

Bosons

Particles with zero or whole number spin do not obey this principle. They are called bosons, because they obey Bose-Einstein statistics.

Baryons

The nucleons and the heavier particles such as lambda and kaon which decay to nucleons are called baryons, meaning heavy.

Leptons

The particles that do not interact strongly with nucleons are called leptons, meaning small, and they include the electron, the tau and the neutrino.

Mesons

By the 1960s many mid-sized particles called mesons were discovered, whose masses were mostly less than nucleon masses but more than the electron mass. The strongly interacting ones are π mesons, or pions, and the weakly interacting ones are μ mesons, or muons.

Why Quarks Were Needed

Both beta decay processes provide evidence that protons and neutrons are not fundamental. The discovery of so many particles led to the conclusion that they must be made of even smaller constituents, which were named quarks.

Hadrons and Leptons

Particles can be classified by whether or not they interact through the strong force. Those that experience the strong force are hadrons, and those that do not are leptons.

Examples

Protons, neutrons and pions are hadrons; electrons and neutrinos are leptons.

Two Kinds of Hadron

Hadrons are composite particles. Some are bosons, called mesons, such as the pion; others are fermions, called baryons, of which the proton and the neutron are the key examples.

Quark Content

Baryons are made of an odd number of quarks, usually three, and mesons are made of an even number, usually one quark and one anti-quark.

Properties of the Leptons

The leptons interact only through the weak or the electromagnetic interaction. No experiment has revealed any internal structure for them, so they appear to be truly fundamental. All known leptons have spin $1/2$, so they are all fermions.

The Six Leptons

They are grouped as three pairs, each pair holding a charged particle, its associated neutrino and the corresponding anti-particles.

Family	Particle	Mass (MeV/c ²)	Charge	Anti-particle
Electron	electron, e^-	0.511	-1	e^+
Electron	electron neutrino	≈ 0	0	anti-neutrino
Muon	muon, μ^-	105.7	-1	μ^+
Muon	muon neutrino	≈ 0	0	anti-neutrino
Tau	tau, τ^-	1777	-1	τ^+
Tau	tau neutrino	≈ 0	0	anti-neutrino

The lepton family

How They Behave

Charged leptons can combine with other particles to form composite particles such as atoms and positronium, while neutrinos rarely interact with anything and are consequently rarely observed. The best known of all the leptons is the electron.

LQ 8 ends here

SHORT QUESTIONS

SQ 12.5.1 What is meant by a fundamental particle?

Definition

A particle that has no internal structure, which means it cannot be divided. Quarks and leptons are at present taken to be the fundamental constituents of matter.

SQ 12.5.2 What is a strange particle, and how is one made?

Strange Particles

Particles that the original theoretical scheme could not account for. They are always created in pairs.

Example

A pion striking a proton creates a kaon and a lambda particle.



SQ 12.5.3 What is Pauli's exclusion principle and which particles obey it?

Principle

Only one particle of a kind may occupy a given quantum state.

Who Obeys It

The half-spin particles, which are called fermions — electrons, protons, neutrons and the other baryons.

SQ 12.5.4 How are baryons and mesons distinguished by their quark content?

Baryons

They are made of an odd number of quarks, usually three.

Mesons

They are made of an even number, usually one quark and one anti-quark.

SQ 12.5.5 Why are neutrinos so rarely observed?

Reason

They are uncharged, of very small mass, and they interact only through the weak interaction. They therefore pass through matter almost without interacting at all.

MCQ 12.5.1 A particle with no internal structure is said to be:

- A composite B strange
C fundamental D hadronic

SOLUTION: Quarks and leptons are the fundamental particles.

MCQ 12.5.2 Particles that experience the strong force are called:

- A hadrons B leptons
C bosons D photons

SOLUTION: Protons, neutrons and pions are hadrons.

MCQ 12.5.3 The characteristic spin of the electron, the proton and the neutron is:

- A 1 B 1/2
C 0 D 2

SOLUTION: They are therefore all fermions.

MCQ 12.5.4 Which of these is a lepton?

- A the neutrino B the proton
C the pion D the kaon

SOLUTION: Leptons do not experience the strong force.

MCQ 12.5.5 A meson is made of:

- A three quarks B two leptons
C a quark and a lepton D a quark and an anti-quark

SOLUTION: That is why it has integral spin and is a boson.

Topic 12.6 Quarks

The Proposal

In 1964 M. Gell-Mann and George Zweig proposed that none of the hadrons, not even the proton and the neutron, are truly fundamental. Instead they are made of combinations of more fundamental entities called quarks, or quark flavours.

The First Three

The three quarks originally proposed were named up, down and strange.

All Six

We are now aware of six quarks, just as there are six leptons, on a presumed symmetry in nature. The other three are called charm, bottom and top.

Quark	Symbol	Charge	Anti-quark
Up	u	+2/3 e	$\bar{u}$
Down	d	-1/3 e	$\bar{d}$
Charm	c	+2/3 e	$\bar{c}$
Strange	s	-1/3 e	$\bar{s}$
Top	t	+2/3 e	$\bar{t}$
Bottom	b	-1/3 e	$\bar{b}$

The six flavours of quark

Charge

All quarks have a spin and an electric charge which is a fraction of the charge on an electron. Quarks are never seen on their own.

LQ 6 starts here — Describe protons and neutrons in terms of their quark composition.

Mesons

A meson consists of a quark and an anti-quark pair. For example, a π^+ meson is an up quark with an anti-down quark.

$$q(u\bar{d}) = +\frac{2}{3} + \frac{1}{3} = +1$$

Baryons

Each baryon consists of three quarks. The proton has the composition uud , so its charge quantum number is

$$q(uud) = \frac{2}{3} + \frac{2}{3} - \frac{1}{3} = +1$$

The Neutron

The neutron has the composition udd , so its charge quantum number is

$$q(udd) = \frac{2}{3} - \frac{1}{3} - \frac{1}{3} = 0$$

LQ 6 ends here

Colour

Not long after the quark theory was proposed it was suggested that quarks carry another property called colour, or colour charge, analogous to electric charge.

The Three Colours

Each flavour of quark can have one of three colours, usually designated red, green and blue. The anti-quarks are anti-red, anti-green and anti-blue. The names colour and flavour have nothing to do with our senses; they are purely whimsical.

Colourless Baryons

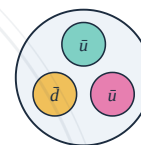
Baryons are made of three quarks, one of each colour.



neutron
proton
Colourless baryons: red + green + blue = white

Colourless baryons: red + green + blue = white

Colourless Anti-Baryons



anti-proton
A colourless anti-baryon: anti-red + anti-green + anti-blue = white

A colourless anti-baryon: anti-red + anti-green + anti-blue = white

Colourless Mesons

A meson consists of a quark of a particular colour and its anti-colour. Both baryons and mesons are therefore colourless, or white.

The Colour Force

The strong force between quarks is referred to as the colour force. This theory of the strong force is called quantum chromodynamics, to indicate that the force acts between colour charges and not between electric charges.

Between Hadrons

The strong force between two hadrons is considered to be a force between the quarks that make them up.

Beta Decay in Terms of Quarks

When a neutron in the nucleus decays into a proton and an electron, an anti-neutrino is also produced.

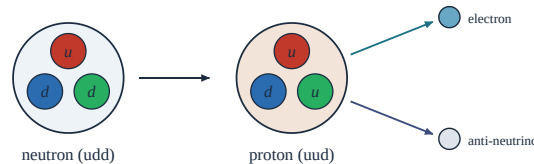
$${}_0^1n \rightarrow {}_1^1p + {}_0^0e + \bar{\nu}$$

What Changes

A neutron of composition udd becomes a proton of composition uud by changing a down quark into an up quark.

$$d \rightarrow u + e^- + \bar{\nu}$$

Diagram



In beta-minus decay a down quark turns into an up quark

Beta-minus decay written at the level of the quarks

What It Shows

The quark model not only deepens our understanding of the structure of particles but also gives insight into their interactions.

SHORT QUESTIONS

SQ 12.6.1 Who proposed the quark model, and in which year?

Gell-Mann and Zweig

They proposed in 1964 that the hadrons are not fundamental but are made of quarks.

MCQ 12.6.2 Name the six quark flavours and give their charges.

Charge $+2/3 e$

Up, charm and top.

Charge $-1/3 e$

Down, strange and bottom.

MCQ 12.6.3 Work out the charge of the proton from its quark composition.

Working

The proton is uud

$$q = \frac{2}{3} + \frac{2}{3} - \frac{1}{3} = +1$$

MCQ 12.6.4 Work out the charge of the neutron from its quark composition.

Working

The neutron is udd

$$q = \frac{2}{3} - \frac{1}{3} - \frac{1}{3} = 0$$

MCQ 12.6.5 What is colour charge, and why are hadrons colourless?

Colour Charge

A property of a quark analogous to electric charge. Each flavour can carry one of three colours: red, green or blue.

Baryons

They hold one quark of each colour, so the three add to white.

Mesons

They hold a colour and its anti-colour, so they too are colourless.

MCQ 12.6.6 Write beta-minus decay at the level of the quarks.

Working

A neutron udd becomes a proton uud , so one down quark becomes an up quark.

$$d \rightarrow u + e^- + \bar{\nu}$$

MCQ 12.6.7 What is quantum chromodynamics?

Definition

The theory of the strong force as a force acting between colour charges rather than between electric charges. The force between quarks is therefore called the colour force.

MCQ 12.6.1 The quark model was proposed in 1964 by:

- | | |
|------------------------------|-----------------------|
| A Dirac and Anderson | B Reines and Cowan |
| C Gell-Mann and Zweig | D Bohr and Rutherford |

SOLUTION: They proposed three quarks: up, down and strange.

MCQ 12.6.2 The charge on an up quark is:

- | | |
|------------|------------|
| A $-1/3 e$ | B $+2/3 e$ |
| C $+1 e$ | D $-1 e$ |

SOLUTION: The down quark carries $-1/3 e$.

MCQ 12.6.3 The quark composition of a neutron is:

- | | |
|---------|---------------------------|
| A uud | B udd |
| C uds | D ud |

SOLUTION: Its charge works out at zero.

MCQ 12.6.4 In beta-minus decay, at the quark level:

- | | |
|---|--------------------------|
| A an up quark becomes a down quark | B a quark is destroyed |
| C a down quark becomes an up quark | D a quark changes colour |

SOLUTION: The neutron udd becomes the proton uud .

MCQ 12.6.5 A baryon is colourless because it holds:

- | | |
|---|-----------------------------------|
| A one quark of each of the three colours | B three quarks of the same colour |
| C a colour and its anti-colour | D no colour charge at all |

SOLUTION: Red plus green plus blue makes white.

MCQ 12.6.6 The theory of the strong force between colour charges is called:

- | | |
|---------------------------|---------------------------------|
| A quantum electrodynamics | B string theory |
| C the standard model | D quantum chromodynamics |

SOLUTION: The force between quarks is called the colour force.

Topic 12.7 Higgs Boson

The Fundamental Particles

They are considered to be the six quarks, the six leptons and the gauge bosons, which are the carriers of the fundamental forces.

How Particles Interact

Leptons and quarks interact with each other by sending and receiving bosons.

Examples

- Electromagnetic interactions occur when two charged particles exchange photons.
- The attraction between two quarks in a nucleus occurs when they exchange gluons.
- The W^+ , W^- and Z are the bosons that carry the weak nuclear force.
- Gravitons are the carriers of the gravitational force.

The Higgs Boson

The Higgs boson is a special particle discovered in 2012 at the Large Hadron Collider at CERN. It is associated with the Higgs field, which permeates all of space.

What It Does

Its crucial role is that it explains how the other particles get their mass by interacting with the Higgs field.

Which Particles Get Mass

The particles that interact strongly with the Higgs field get more mass, such as the carriers of the electroweak interaction, the W^+ , W^- and Z bosons. Particles like photons do not interact with the field, so their rest mass is zero.

Its Own Mass

$$m \approx 125 \text{ GeV}/c^2$$

It decays rapidly into other particles.

Key Facts

- The Higgs boson gets its own mass from its interaction with its associated Higgs field.
- It can be a unique portal to the conditions of the universe shortly after the Big Bang, and to signs of dark matter.

SHORT QUESTIONS

MCQ 12.7.1 Name the exchange particle for each of the four forces.

Carriers

The electromagnetic force is carried by photons.

The strong nuclear force is carried by gluons.

The weak nuclear force is carried by the W and Z bosons.

Gravity is carried by gravitons.

MCQ 12.7.2 When and where was the Higgs boson discovered?

Discovery

In 2012 at the Large Hadron Collider at CERN.

MCQ 12.7.3 Why is the rest mass of a photon zero?

Reason

A particle gets its mass by interacting with the Higgs field. The photon does not interact with that field at all, so its rest mass is zero.

MCQ 12.7.4 What is the mass of the Higgs boson?

Value

$$m \approx 125 \text{ GeV}/c^2$$

It decays rapidly into other particles.

MCQ 12.7.1 The exchange particle of the electromagnetic force is the:

- A photon B gluon
C graviton D W boson

SOLUTION: Two charged particles interact by exchanging photons.

MCQ 12.7.2 The strong force between quarks is carried by:

- A photons B gravitons
C Z bosons D gluons

SOLUTION: Gluons hold the quarks inside a hadron.

MCQ 12.7.3 The Higgs boson was discovered at CERN in:

- A 2002 B 2012
C 1995 D 2015

SOLUTION: It was found at the Large Hadron Collider.

MCQ 12.7.4 The mass of the Higgs boson is about:

- A 125 MeV/c² B 0.511 MeV/c²
C 125 GeV/c² D 931 MeV/c²

SOLUTION: It decays rapidly into other particles.

Topic 12.8 Conservation Laws**What They Cover**

All nuclear processes, both nuclear reactions and nuclear decays, obey conservation laws.

The Laws

- Conservation of energy, momentum and charge, which includes the nucleon number A and the charge number Z .
- Conservation of baryon number.
- Conservation of lepton number.

Hadrons

The hadrons include the mesons, such as pions and kaons, and the baryons, such as protons, neutrons, omega, sigma and the lambda particle.

Non-Hadrons

They are the leptons, including electrons, muons and neutrinos.

SHORT QUESTIONS**SQ 12.8.1** List the conservation laws obeyed by all nuclear processes.**The Laws**

Conservation of energy, momentum and charge, which includes the nucleon number A and the charge number Z .

Conservation of baryon number.
Conservation of lepton number.

SQ 12.8.2 Name two hadrons and two non-hadrons.**Hadrons**

Protons and neutrons, which are baryons; pions and kaons, which are mesons.

Non-Hadrons

Electrons and neutrinos, which are leptons. Muons are leptons too.

SQ 12.8.3 Check whether nucleon number and charge are conserved in the decay of a neutron.**Working**

$${}_0^1n \rightarrow {}_1^1p + {}_{-1}^0e + \bar{\nu}$$

Nucleon Number

$$1 = 1 + 0 + 0$$

Charge

$$0 = +1 - 1 + 0$$

Both are conserved.

MCQ 12.8.1 Which of these is not conserved in a nuclear process?

- A the nucleon number B the charge number
C the number of neutrons D the lepton number

SOLUTION: A neutron may turn into a proton, so their separate numbers change.

MCQ 12.8.2 Baryons include:

- A protons and neutrons B pions and kaons
C electrons and muons D photons

SOLUTION: Pions and kaons are mesons; electrons and muons are leptons.

MCQ 12.8.3 In the decay of a free neutron, the total charge before and after is:

- A +1 before and 0 after B zero in both cases
C 0 before and +1 after D −1 in both cases

SOLUTION: The proton and the electron cancel.

Topic 12.9 The Asymmetry of Matter and Anti-Matter in the Universe**The Observation**

Many observations show that there is an asymmetry between matter and anti-matter, and this is one of the most remarkable features of our universe.

What the Universe Holds

The universe is assumed to be composed of about 5% ordinary matter — electrons, protons and neutrons — of which 71% is hydrogen atoms and 24% helium atoms. There is no contribution at all from anti-hydrogen or anti-helium.

The Explanation Offered

The experimental results explain that the asymmetry is due to the violation of the conservation of baryon number, that is, an imbalance in the numbers of baryons and anti-baryons.

If Symmetry Is Also Violated

If the particle and anti-particle symmetry is also violated, there is a mechanism for making more quarks than anti-quarks, more leptons than anti-leptons and eventually more matter than anti-matter.

Still Unsolved

It is concluded that the asymmetry of matter and anti-matter remains a mystery.

SHORT QUESTIONS**SQ 12.9.1** What is the observed composition of the ordinary matter of the universe?**Composition**

Of the 5% that is ordinary matter, about 71% is hydrogen atoms and 24% helium atoms, with no contribution at all from anti-hydrogen or anti-helium.

SQ 12.9.2 Which conservation law must be violated to explain the matter-antimatter asymmetry?**Baryon Number**

The experimental results explain the asymmetry by a violation of the conservation of baryon number, that is, an imbalance between the numbers of baryons and anti-baryons.

SQ 12.9.3 Is the asymmetry of matter and anti-matter understood?**No**

A number of hypotheses exist, but the asymmetry of matter and anti-matter is still an unsolved mystery.

MCQ 12.9.1 Of the ordinary matter of the universe, hydrogen atoms make up about:

- A 24% B 5%
C 68% D 71%

SOLUTION: Helium makes up about 24%.

MCQ 12.9.2 The asymmetry of matter and anti-matter is attributed to a violation of the conservation of:

- A charge B energy
C baryon number D momentum

SOLUTION: It means an imbalance of baryons and anti-baryons.

MCQ 12.9.3 The problem of the matter-antimatter asymmetry is:

- | | |
|-------------------|-------------------------|
| A fully explained | B of no interest |
| C solved in 2012 | D still unsolved |

SOLUTION: A number of hypotheses exist but none is established.

Topic 12.10 Most of the Matter in the Observable Universe Is Plasma**What We Know**

Our universe is more vast than our thinking, because we still know only about 5% of it.

What We Do Not Know

The universe consists of about 27% of unknown matter called dark matter and about 68% of a mysterious antigravity material known as dark energy. Together those make 95% of the universe, about which we know nothing.

The 5% We Do Know

It is ordinary matter, in which hydrogen and helium are almost entirely in the plasma state.

The Conclusion

About 95% of that 5% of the observable universe is in the plasma state, while the remaining 5% of it is in the form of matter. Hence most of the matter in the observable universe is plasma.

SHORT QUESTIONS**SQ 12.10.1 What fraction of the universe do we actually know about?****Only 5%**

The rest is about 27% dark matter and about 68% dark energy, which together make 95% of the universe.

SQ 12.10.2 Why is it said that most of the matter in the observable universe is plasma?**Reason**

In the 5% that is ordinary matter, the hydrogen and the helium are almost entirely in the plasma state — about 95% of that 5%.

SQ 12.10.3 What is dark energy?**Definition**

A mysterious antigravity material that makes up about 68% of the universe and about which nothing else is known.

MCQ 12.10.1 Dark matter makes up about what fraction of the universe?

- | | |
|-------|--------------|
| A 68% | B 27% |
| C 5% | D 95% |

SOLUTION: Dark energy makes up about 68%.

MCQ 12.10.2 In the 5% of the universe that we know, hydrogen and helium are almost entirely:

- | | |
|------------------------------|------------------------------|
| A in the plasma state | B solid |
| C liquid | D in the form of anti-matter |

SOLUTION: That is why most of the observable matter is plasma.

MCQ 12.10.3 Dark energy is described as:

- | | |
|-----------------------------|--|
| A a form of ordinary matter | B a mysterious antigravity material |
| C a kind of plasma | D a heavy lepton |

SOLUTION: Nothing else about it is known.

Topic 12.11 The Theories About the Forces Between the Masses of Particles**Two Theories**

To explain the interactions between the masses of particles through different mediators we have two theories: the quantum field theory and the string theory.

The Quantum Field Theory

Each particle is represented by a field called a quantum field, and it is responsible for transmitting a force from one particle to another by a mediator.

An Example

A positively charged particle produces an electric field in the space around it, and exerts an attractive force on a nearby negatively charged particle through that field.

What the Field Carries

The field can also carry energy and momentum from one particle to another, and the energy and momentum of all fields are quantized.

Field Particles

The quanta that exchange momentum and energy from one type of particle to another are called field particles, and they are all bosons.

The Mediators

- The electromagnetic force is mediated by photons, the quanta of the electromagnetic field.
- The strong nuclear force is mediated by gluons.
- The electroweak force is mediated by the W and Z bosons.
- The gravitational force is mediated by gravitons.

String Theory

String theory is an advanced concept in theoretical physics proposing that the fundamental particles of the universe, instead of being point-like, are actually tiny vibrating strings.

What the Strings Do

These strings can be open or closed loops, and their vibrations determine the properties of the particles, including mass and force.

Its Standing

The string theory framework offers a potential theory of everything, but it still remains unproved experimentally.

SHORT QUESTIONS**SQ 12.11.1 What is a field particle in quantum field theory?****Definition**

The quantum of a field, which exchanges energy and momentum from one particle to another. All field particles are bosons.

SQ 12.11.2 How does quantum field theory describe a force between two particles?**By Exchange**

Each particle is represented by a quantum field, and the force is transmitted from one particle to another by a mediator, the field particle. The field also carries energy and momentum between them.

SQ 12.11.3 What does string theory propose?**Proposal**

That the fundamental particles are not point-like but tiny vibrating strings, open or closed loops, whose vibrations determine the properties of the particle, including its mass and force.

SQ 12.11.4 What is the standing of string theory?**Unproved**

It offers a potential theory of everything, but it still remains unproved experimentally.

MCQ 12.11.1 In quantum field theory, the quanta that carry a force are all:

- | | |
|-----------------|-----------|
| A fermions | B leptons |
| C bosons | D quarks |

SOLUTION: Photons, gluons, W and Z bosons and gravitons are all bosons.

MCQ 12.11.2 String theory proposes that fundamental particles are:

- | | |
|---------------------------------|-------------------------|
| A tiny vibrating strings | B point-like |
| C made of quarks only | D fields with no quanta |

SOLUTION: The vibration decides the mass and the force.

MCQ 12.11.3 String theory at present is:

- | | |
|------------------------------|----------------------------------|
| A fully confirmed | B abandoned |
| C part of the standard model | D unproved experimentally |

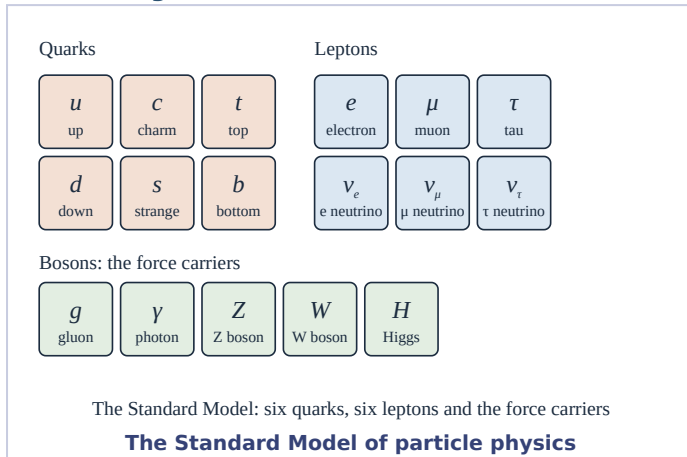
SOLUTION: It offers a potential theory of everything.

Topic 12.12 The Standard Model

What It Is

The standard model is the collection of theories that describe the smallest experimentally observed particles of matter and the interaction between energy and matter.

Three Categories



Matter

Matter, which makes up only 5% of the universe, is composed of quarks and leptons.

The Fundamental Bosons

They provide three forces: electromagnetism, the strong nuclear force and the weak nuclear force.

The Higgs Boson

It provides the explanation for how the other particles get their mass.

Still Incomplete

The model is still considered incomplete. It is at present unable to explain several important features of the known universe:

- Gravity.
- Dark matter, which is 27% of the universe.
- Dark energy, which is 68% of the universe.

SHORT QUESTIONS

SQ 12.12.1 What three categories of particle make up the standard model?

Categories

Quarks and leptons, which make up matter, and the bosons, which carry the forces.

SQ 12.12.2 Which forces does the standard model account for, and which does it not?

Accounted For

Electromagnetism, the strong nuclear force and the weak nuclear force.

Not Accounted For

Gravity, and also dark matter and dark energy.

SQ 12.12.3 Why is the standard model called incomplete?

Reason

It cannot explain gravity, nor dark matter, which is 27% of the universe, nor dark energy, which is 68%. Between them those are 95% of the universe.

MCQ 12.12.1 Matter in the standard model is composed of:

- A quarks and leptons B quarks and bosons
C leptons and photons D bosons only

SOLUTION: The bosons are the force carriers.

MCQ 12.12.2 The standard model cannot explain:

- A electromagnetism B the strong nuclear force
C the weak nuclear force D gravity

SOLUTION: It also fails on dark matter and dark energy.

MCQ 12.12.3 Matter makes up what fraction of the universe?

- A 27% B 5%
C 68% D 95%

SOLUTION: The rest is dark matter and dark energy.

Chapter Exercise

SQ 12.1 What do different isotopes of a given element have in common? How are they different?

In Common

The same number of protons, so the same atomic number Z and the same chemical behaviour.

Different

Different numbers of neutrons, so a different mass number A .

Example

Carbon has the isotopes $^{12}_6\text{C}$, $^{13}_6\text{C}$ and $^{14}_6\text{C}$.

SQ 12.2 Identify the element that has 87 nucleons and 50 neutrons.

Working

$$A = 87$$

$$N = 50$$

$$Z = A - N = 87 - 50 = 37$$

The Element

The atomic number 37 belongs to rubidium, so the nuclide is $^{87}_{37}\text{Rb}$.

SQ 12.3 What are the similarities and differences between the strong nuclear force and the electromagnetic force?

Similarities

Both are much stronger than gravity, and both act between the particles of matter.

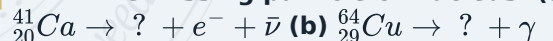
Strong Nuclear Force || Electromagnetic Force

It is the strongest of the four forces. || It is about 10^2 times weaker.

Its range is less than 10^{-15} m. || Its range is infinite. It acts between all nucleons. || It acts only on charged particles.

It is always attractive between nucleons. || It is attractive or repulsive.

SQ 12.4 Fill in the missing particle or nucleus: (a)



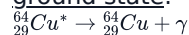
Part (a)

This is a beta-minus decay, so the mass number is unchanged and the atomic number rises by one.



Part (b)

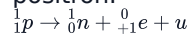
Gamma emission changes neither the mass number nor the atomic number; only the excited nucleus falls to its ground state.



SQ 12.5 Why must a neutrino be released in positron emission?

Conservation

In positron emission a proton becomes a neutron and a positron.



Why the Neutrino

Without it, lepton number would not be conserved, since a positron has lepton number -1 . It also carries away the missing share of the energy, which is why the positron spectrum is continuous.

SQ 12.6 Distinguish between fermions and bosons.

Fermions

They have half integral spin.

Bosons

They have zero or whole number spin.

Fermions	Bosons
They obey Pauli's exclusion principle.	They do not obey it.
They obey Fermi-Dirac statistics.	They obey Bose-Einstein statistics.
Electrons, protons, neutrons, baryons.	Photons, pions, mesons.

SQ 12.7 How does the strong force hold the nucleus?

The Problem

The protons in a nucleus repel each other electrically, so some stronger attraction is needed.

The Strong Force

It is the strongest of the four forces and it acts attractively between all nucleons — proton and proton, neutron and neutron, and proton and neutron.

Range

It is a short-range force, of range less than 10^{-15} m, so it acts only inside the nucleus, where it overcomes the electric repulsion.

SQ 12.8 Can there be pair production for a photon having an energy of 20 keV? Explain briefly.

No

The minimum energy needed is the sum of the rest mass energies of the electron and the positron.

$$E = 2m_e c^2 = 1.02 \text{ MeV}$$

Comparison

20 keV is only 0.02 MeV, which is far below the threshold, so no pair can be created.

SQ 12.9 What is the difference between a beta particle and an electron?

The Same Particle

A beta particle is an electron; the two are indistinguishable once emitted.

The Difference Is Where It Comes From

An orbital electron already exists outside the nucleus, while a beta particle is created within the nucleus at the moment of emission, when a neutron turns into a proton.

SQ 12.10 How do a proton and a neutron convert into each other?

Neutron Into Proton

This is beta-minus decay.

$${}_0^1n \rightarrow {}_1^1p + {}_{-1}^0e + \bar{\nu}$$

Proton Into Neutron

This is beta-plus decay.

$${}_1^1p \rightarrow {}_0^1n + {}_{+1}^0e + \nu$$

At the Quark Level

A down quark changes into an up quark, or the reverse.

SQ 12.11 Why does beta decay have a continuous energy spectrum while alpha decay has a discrete one?

Alpha Decay

Only two bodies are produced, so the sharing of the disintegration energy is fixed and every alpha particle carries the same energy.

Beta Decay

Three bodies are produced, so the energy is shared between the beta particle and the anti-neutrino in varying proportions. The beta energy can be anything from zero up to a maximum.

SQ 12.12 Differentiate between hadrons and leptons with examples.

Hadrons	Leptons
They <u>experience the strong force</u> .	They do not experience it.
They are composite, made of quarks.	They appear to be truly <u>fundamental</u> .
They are mesons or baryons.	They all have spin 1/2.

Hadrons	Leptons
Protons, neutrons, pions.	Electrons, muons, neutrinos.

SQ 12.13 Why can an electron-positron pair not decay into a single photon?

Momentum

In the frame in which the pair is at rest the total momentum is zero, but a single photon always carries momentum E/c , which cannot be zero.

Conclusion

Momentum could not be conserved, so at least two photons must be produced.

SQ 12.14 State the role of the Higgs boson in the generation of mass.

The Higgs Field

The Higgs boson is associated with the Higgs field, which permeates all of space.

How Mass Arises

Particles acquire their mass by interacting with this field. Those that interact strongly with it, such as the W and Z bosons, gain a large mass, while photons do not interact with it at all and so have zero rest mass.

SQ 12.15 What are mesons? Give examples.

Mesons

Hadrons that are bosons, made of an even number of quarks, usually one quark and one anti-quark.

Mass

Their masses are mostly less than a nucleon mass but more than an electron mass.

Examples

The pion π and the kaon K .

CRQ 12.1 Is a meson a boson or a fermion? Give a reason.

A Boson

A meson is made of one quark and one anti-quark, each of spin 1/2, so its total spin is zero or a whole number.

Consequence

Having integral spin, it does not obey Pauli's exclusion principle and obeys Bose-Einstein statistics, which is what makes it a boson.

CRQ 12.2 Why does an alpha emitter emit alpha particles instead of four separate nucleons?

Binding Energy

The helium nucleus is an exceptionally tightly bound group of two protons and two neutrons.

Energy Balance

Emitting the four nucleons separately would take far more energy than the decay can supply, while emitting them already bound as an alpha particle releases energy. So the alpha particle is the form the decay can actually take.

CRQ 12.3 Which is more energetic, alpha decay or beta decay? Justify your answer.

Alpha Decay

An alpha particle typically carries several MeV, and every one from a given nuclide carries the same sharply defined energy.

Beta Decay

The disintegration energy is shared with the anti-neutrino, so the beta particle carries anything from zero up to a maximum which is usually smaller than the alpha energy.

Conclusion

Alpha decay is the more energetic per emitted particle.

CRQ 12.4 A nucleus undergoes gamma decay, emitting a gamma ray photon with an energy of 1.5 MeV. Calculate (i) the frequency (ii) the wavelength (iii) the momentum of the gamma ray.

Given Data

$$E = 1.5 \text{ MeV} = 1.5 \times 10^6 \times 1.6 \times 10^{-19} = 2.4 \times 10^{-13} \text{ J}$$

Frequency

$$E = hf$$

$$f = \frac{2.4 \times 10^{-13}}{6.63 \times 10^{-34}} = 3.62 \times 10^{20} \text{ Hz}$$

Wavelength

$$\lambda = \frac{c}{f} = \frac{3 \times 10^8}{3.62 \times 10^{20}} = 8.29 \times 10^{-13} \text{ m}$$

Momentum

$$p = \frac{E}{c} = \frac{2.4 \times 10^{-13}}{3 \times 10^8} = 8 \times 10^{-22} \text{ kg ms}^{-1}$$

CRQ 12.5 Why do alpha particles not make physical contact with the nucleus when headed directly towards it?

Coulomb Repulsion

Both the alpha particle and the nucleus are positively charged, so as the alpha particle approaches, the repulsive force rises as the inverse square of the separation.

The Turning Point

At the distance of closest approach the whole kinetic energy of the alpha particle has been turned into electrical potential energy, so it stops and is turned back before the short-range strong nuclear force can reach it.

MCQ 12.1 Which one of the following is a fundamental particle?

A	Proton	B	Neutron
C	Electron	D	Meson

SOLUTION: Correct answer: (c) Electron.

MCQ 12.2 The first discovered anti-particle is the:

A	anti-proton	B	anti-neutrino
C	anti-photon	D	anti-electron

SOLUTION: Correct answer: (d) anti-electron.

MCQ 12.3 Which one of the following pairs of particles creates annihilation?

A	proton-proton	B	proton-neutron
C	neutron-photon	D	electron-positron

SOLUTION: Correct answer: (d) electron-positron.

MCQ 12.4 The strong nuclear force between two particles is mediated by:

A	gluons	B	photons
C	mesons	D	gravitons

SOLUTION: Correct answer: (a) gluons.

MCQ 12.5 Which one of the following forces acts between two particles through photons?

A	Strong nuclear force	B	Weak force
C	Electromagnetic force	D	Gravitational force

SOLUTION: Correct answer: (c) Electromagnetic force.

MCQ 12.6 When a neutron changes into a proton, we observe:

A	β^- decay	B	β^+ decay
C	γ decay	D	α decay

SOLUTION: Correct answer: (a) β^- decay.

MCQ 12.7 A baryon is formed by a combination of:

A	2 quarks	B	3 quarks
C	4 quarks	D	a quark and an anti-quark

SOLUTION: Correct answer: (b) 3 quarks.

MCQ 12.8 Which one of the following forces has a negligible effect between elementary particles?

A	Strong nuclear force	B	Weak force
C	Gravitational force	D	Electromagnetic force

SOLUTION: Correct answer: (c) Gravitational force.

MCQ 12.9 Which particles are produced by the strong interaction?

A	Gravitons	B	Leptons
C	Hadrons	D	Muons

SOLUTION: Correct answer: (c) Hadrons.

MCQ 12.10 A strong nuclear force exists between the nucleons:

A	$p-p$	B	$n-n$
C	$p-n$	D	all of these

SOLUTION: Correct answer: (d) all of these.

MCQ 12.11 Which one of the following radiations has the highest ionization power?

A	α	B	β
C	γ	D	all are equal

SOLUTION: Correct answer: (a) α .

MCQ 12.12 Which one of the following radiations has the highest penetrating power?

A	α	B	β
C	γ	D	all are equal

SOLUTION: Correct answer: (c) γ .

MCQ 12.13 A change occurs in the atomic number of a nucleus but its mass number remains the same by the decay of:

A	α	B	β
C	γ	D	α and γ

SOLUTION: Correct answer: (b) β .

MCQ 12.14 In a nucleus a neutron changes into a proton and the atomic number changes by one. The mass number will:

A	decrease	B	increase
C	remain the same	D	none of these

SOLUTION: Correct answer: (c) remain the same.

MCQ 12.15 The electroweak theory was introduced by:

A	Dirac	B	Einstein
C	Anderson	D	Dr. Abdus Salam

SOLUTION: Correct answer: (d) Dr. Abdus Salam.

MCQ 12.16 The asymmetry of matter and anti-matter is due to an imbalance in the number of:

A	hadrons	B	leptons
C	baryons	D	photons

SOLUTION: Correct answer: (c) baryons.

MCQ 12.17 Which one of the following particles is responsible for the mass of the fundamental particles?

A	Quarks	B	Anti-quarks
C	Leptons	D	Higgs boson

SOLUTION: Correct answer: (d) Higgs boson.

MCQ 12.18 A proton is composed of up and down quarks. The order of the quarks is:

A	udd	B	udu
C	uud	D	dud

SOLUTION: Correct answer: (c) uud.

MCQ 12.19 The number of quarks that compose a neutron is:

A	2	B	3
C	4	D	5

SOLUTION: Correct answer: (b) 3.

Numerical 12.1 Uranium-238 is an alpha emitter. In the process it is transmuted into a daughter nucleus. What are the mass number A and the charge number Z of the daughter nucleus, and what is its chemical symbol? [Ans: $A = 234$, $Z = 90$, thorium (Th)]

Given Data

The parent nuclide is

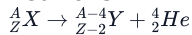


To Find

The mass number, the charge number and the symbol of the daughter

Formula

In alpha decay the nucleus loses two protons and two neutrons.

**Solution**

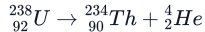
The mass number of the daughter is

$$A = 238 - 4 = 234$$

The charge number of the daughter is

$$Z = 92 - 2 = 90$$

The element of atomic number 90 is thorium.

**Result**

$$A = 234$$

$$Z = 90$$

thorium (Th)

Numerical 12.2 Polonium ${}_{84}^{218}Po$ is a beta-minus emitter. What will be the mass number A and the charge number Z of the daughter nucleus? (Ans: $A = 218, Z = 85$)

Given Data

The parent nuclide is

**To Find**

The mass number and the charge number of the daughter

Formula

In beta-minus decay a neutron becomes a proton, so no nucleon is lost.

**Solution**

The mass number is unchanged.

$$A = 218$$

The charge number rises by one.

$$Z = 84 + 1 = 85$$

**Result**

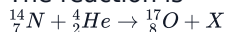
$$A = 218$$

$$Z = 85$$

Numerical 12.3 Nitrogen ${}_{7}^{14}N$ bombarded by an alpha particle results in ${}_{8}^{17}O$. What is the product particle in this nuclear reaction? (Ans: ${}_1^1H$, a proton)

Given Data

The reaction is

**To Find**

The particle X

Formula

The nucleon number and the charge number are conserved.

Solution

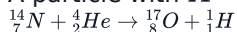
For the mass number of the missing particle

$$A = (14 + 4) - 17 = 1$$

For the charge number of the missing particle

$$Z = (7 + 2) - 8 = 1$$

A particle with $A = 1$ and $Z = 1$ is a proton.

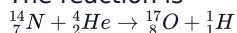
**Result**

The product particle is a proton, ${}_1^1H$.

Numerical 12.4 Show that the nucleon number A and the charge number Z are conserved in numerical question 12.3.

Given Data

The reaction is

**To Find**

That A and Z balance on the two sides

Solution

Nucleon number on the left

$$A = 14 + 4 = 18$$

Nucleon number on the right

$$A = 17 + 1 = 18$$

Charge number on the left

$$Z = 7 + 2 = 9$$

Charge number on the right

$$Z = 8 + 1 = 9$$

Result

Both the nucleon number and the charge number are the same on the two sides, so both are conserved.

Numerical 12.5 Determine the rest mass energy of an electron in eV. Its rest mass is 0.000555 u. (Ans: 0.517 MeV)

Given Data

$$m_o = 0.000555 u$$

$$1 u = 931 \text{ MeV}$$

To Find

The rest mass energy $E_o = ?$

Formula

$$E_o = m_o c^2$$

Solution

Working on the unified mass scale

$$E_o = 0.000555 \times 931 = 0.517 \text{ MeV}$$

In electron volt

$$E_o = 5.17 \times 10^5 \text{ eV}$$

Result

$$E_o = 0.517 \text{ MeV}$$

Numerical 12.6 Calculate the Q-value for the reaction taking place in Rutherford's experiment on the artificial disintegration of nitrogen by bombardment with alpha particles. The relative masses are ${}_{7}^{14}N = 14.007515 u$, ${}_2^4He = 4.003837 u$, ${}_8^{17}O = 17.004533 u$ and ${}_1^1H = 1.008142 u$. (Ans: -1.23 MeV)

Given Data

$$m({}_{7}^{14}N) = 14.007515 u$$

$$m({}_2^4He) = 4.003837 u$$

$$m({}_8^{17}O) = 17.004533 u$$

$$m({}_1^1H) = 1.008142 u$$

To Find

The Q-value of the reaction

Formula

The Q-value is the mass lost, expressed as energy.

$$Q = [m_{\text{before}} - m_{\text{after}}] \times 931 \text{ MeV}$$

Solution

The total mass before the reaction is

$$m_{\text{before}} = 14.007515 + 4.003837 = 18.011352 u$$

The total mass after the reaction is

$$m_{\text{after}} = 17.004533 + 1.008142 = 18.012675 u$$

So the change of mass is

$$\Delta m = 18.011352 - 18.012675 = -0.001323 u$$

And the Q-value is

$$Q = -0.001323 \times 931 = -1.23 \text{ MeV}$$

Result

$$Q = -1.23 \text{ MeV}$$

Meaning

The Q-value is negative, so the reaction is endothermic: energy has to be supplied for it to take place.

Self Test

Seventeen questions across the whole chapter. Work through them without the notes, then check the answers keyed at the foot of the page.

Q 1 The total number of protons and neutrons in a nucleus is the:

- | | |
|------------------------|-------------------------|
| A atomic number | B neutron number |
| C mass number | D charge number |

Q 2 One unified mass unit is equivalent to:

- | | |
|-------------------|------------------|
| A 931 MeV | B 511 keV |
| C 1.02 MeV | D 1 GeV |

Q 3 The strongest of the four fundamental forces is the:

- | | |
|--------------------------------|-------------------------------|
| A gravitational force | B weak nuclear force |
| C electromagnetic force | D strong nuclear force |

Q 4 The force responsible for beta decay is the:

- | | |
|--------------------------------|------------------------------|
| A strong nuclear force | B weak nuclear force |
| C electromagnetic force | D gravitational force |

Q 5 The first anti-particle to be discovered was the:

- | | |
|-----------------------|------------------------|
| A anti-proton | B positron |
| C anti-neutron | D anti-neutrino |

Q 6 The minimum photon energy needed for pair production is:

- | | |
|-------------------|-------------------|
| A 0.51 MeV | B 0.25 MeV |
| C 1.02 MeV | D 931 MeV |

Q 7 In alpha decay the atomic number of the nucleus:

- | | |
|---------------------|-----------------------|
| A falls by 2 | B falls by 4 |
| C rises by 1 | D is unchanged |

Q 8 In beta-minus decay the mass number of the nucleus:

- | | |
|---------------------|-----------------------|
| A falls by 4 | B rises by 1 |
| C falls by 1 | D is unchanged |

Q 9 The radiation with the greatest penetrating power is the:

- | | |
|-------------------------|------------------------|
| A alpha particle | B beta particle |
| C gamma ray | D neutron |

Q 10 Beta particles have a continuous energy spectrum because the energy is shared with the:

- | | |
|----------------------------|------------------------|
| A nucleus | B anti-neutrino |
| C orbital electrons | D gamma ray |

Q 11 Particles that experience the strong force are called:

- | | |
|------------------|------------------|
| A leptons | B photons |
| C hadrons | D bosons |

Q 12 A baryon is made of:

- | | |
|------------------------------------|----------------------|
| A three quarks | B two quarks |
| C a quark and an anti-quark | D four quarks |

Q 13 The quark composition of a proton is:

- | | |
|--------------|--------------|
| A udd | B uds |
| C uud | D ud |

Q 14 The exchange particle of the strong force is the:

- | | |
|------------------|-------------------|
| A photon | B graviton |
| C W boson | D gluon |

Q 15 The particle that explains how the others get their mass is the:

- | | |
|----------------------|-------------------|
| A Higgs boson | B gluon |
| C graviton | D neutrino |

Q 16 Dark energy makes up about what fraction of the universe?

- | | |
|--------------|--------------|
| A 5% | B 27% |
| C 68% | D 95% |

Q 17 The standard model is unable to explain:

- | | |
|-----------------------------------|---------------------------------|
| A electromagnetism | B the weak nuclear force |
| C the strong nuclear force | D gravity |

Answers 1 (c) 2 (a) 3 (d) 4 (b) 5 (b) 6 (c) 7 (a) 8 (d) 9 (c) 10 (b) 11 (c) 12 (a) 13 (c) 14 (d) 15 (a) 16 (c) 17 (d)