Question 1

(*i*) Describe Rutherford's model of the atom.

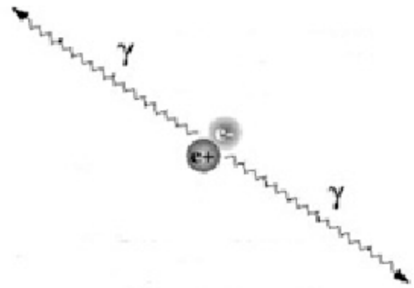
(*j*) ETS Walton is Ireland's only Nobel Prize winner in the sciences. Give two reasons why the Cockcroft and Walton experiment was significant to the understanding of particle physics.

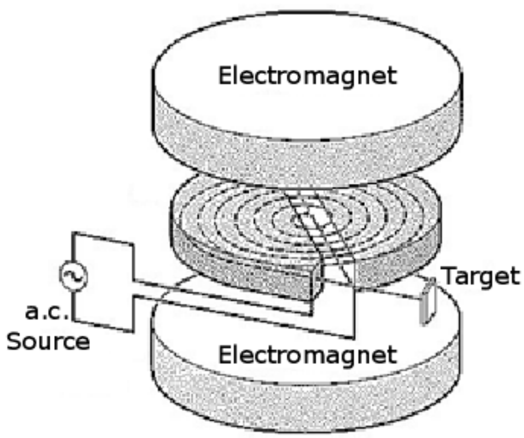
Question 2

(*a*) Read the following passage and answer the accompanying questions.

Cyclotrons and PET Scanners

Positron emission tomography (PET) scanners are designed to detect the pair of photons generated from the annihilation reaction between a positron and an electron. A carbon–11 nucleus, which has a half-life of twenty minutes, decays with the emission of a positron. The positron travels only a short distance before colliding with an electron in the surrounding matter. Pair annihilation occurs. The emitted photons travel in opposite directions.





Cyclotrons are located in the same hospital as the PET scanners and are used to manufacture radioactive nuclei. Cyclotrons are circular devices in which charged particles are accelerated in a spiral path within a vacuum. The particles are accelerated by a rapidly alternating voltage and acquire high kinetic energies. They spiral outwards under the influence of the magnetic field until they have sufficent velocity and are deflected into a target producing radioactive nuclei, including carbon–11.

(Adapted from "*Essentials of Nuclear Medicine Physics*"; Powsner & Powsner; 1998)

(*i*) Electrons are leptons. List the three fundamental forces that electrons experience in increasing order of strength.

(*ii*) Write an equation to represent the pair annihilation described in the text.

(*iii*) Calculate the frequency of each photon produced in this pair annihilation.

(*iv*) Why do the photons produced in pair annihilation travel in opposite directions?

(*v*) Write a nuclear equation to represent the decay of carbon–11.

(*vi*) What is the value of the decay constant of carbon–11?

(*vii*) Explain why the carbon–11 nuclei used in the PET scanner must be produced in a cyclotron in, or close to, the same hospital as the scanner.

(*viii*) Give an expression for the momentum of a particle in the cyclotron in terms of the magnetic flux density of the field, the charge on the particle and the radius of its circular path at any instant.

Question 3

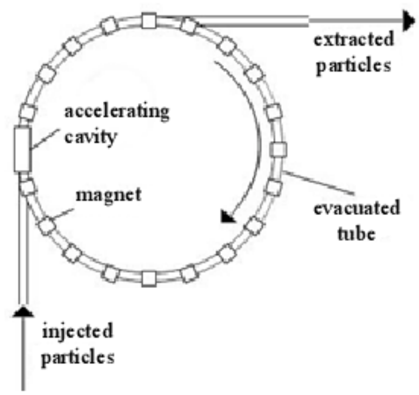
(*a*) In 1932 J.D. Cockroft and E.T.S. Walton accelerated protons to energies of up to 700 keV and used them to bombard a lithium target. They observed the production of alpha-particles from the collisions between the accelerated protons and the lithium nuclei.

How did Cockroft and Walton accelerate the protons?
How did they detect the alpha-particles? (12)

Write the nuclear equation for the reaction that occurred and indicate the historical significance of their observation. (12)

Calculate the speed of a proton that has a kinetic energy of 700 keV. (12)

Many modern particle accelerators, such as the Large Hadron Collider (LHC) in CERN, have a circular design. The diagram shows a simplified design of a circular accelerator.



Why is the tube evacuated? (3)

What is the purpose of accelerating the particles to high velocities? (4)

What is the purpose of the magnets? (4)

Give an advantage of a circular accelerator over a linear accelerator. (3)

Can an accelerator of this design be used to accelerate neutrons? Explain your answer. (6)

Question 4

(*a*) (i) What is a positron? (6)

(ii) When a positron and an electron meet two photons are produced.
Write an equation to represent this interaction. (6)

(iii) Why are photons produced in this interaction?
Explain why two photons are produced.
Calculate the minimum frequency of the photons produced.
Explain why the photons produced usually have a greater frequency than your calculated minimum frequency value. (24)

(iv) Why must two positrons travel at high speeds so as to collide with each other?
How are charged particles given high speeds? (12)

(v) Explain why two positrons cannot annihilate each other in a collision. (8)

Question 5

(*a*) The history of anti-matter begins in 1928 when a young English physicist named **Paul Dirac** predicted an anti-particle for the electron.

(i) What is anti-matter?

An anti-matter particle was first discovered during the study of cosmic rays in 1932.

Name the anti-particle and give its symbol.

What happens when a particle meets its anti-particle? (18)

(ii) What is meant by pair production?

A photon of frequency 3.6×10^{20} Hz causes pair production.

Calculate the kinetic energy of one of the particles produced, each of which has a rest mass of 9.1×10^{-31} kg. (21)

(iii) A member of a meson family consists of two particles.

Each particle is composed of up and down quarks and their anti-particles.

Construct the possible combinations.

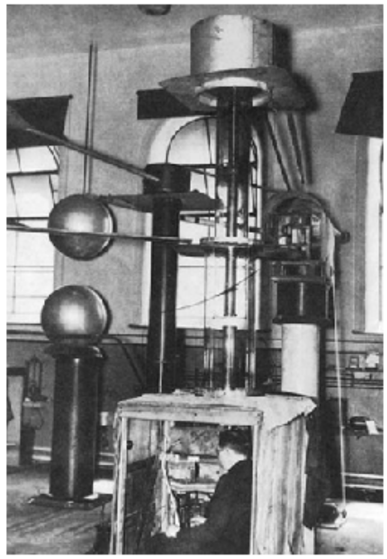
Deduce the charge of each combination and identify each combination.

What famous Irish writer first thought up the name 'quark'? (17)

(speed of light = 3.0×10^{8} m s^{-1}; Planck constant = 6.6×10^{-34} J s)

Question 6

(*a*) In 1932 Cockcroft and Walton succeeded in splitting lithium nuclei by bombarding them with artificially accelerated protons using a linear accelerator.
Each time a lithium nucleus was split a pair of alpha particles was produced.



How were the protons accelerated? How were the alpha particles detected? (8)

Write a nuclear equation to represent the splitting of a lithium nucleus by a proton.
Calculate the energy released in this reaction. (21)

Most of the accelerated protons did not split a lithium nucleus. Explain why. (6)

Cockcroft and Walton's apparatus is now displayed at CERN in Switzerland, where very high energy protons are used in the Large Hadron Collider.

In the Large Hadron Collider, two beams of protons are accelerated to high energies in a circular accelerator. The two beams of protons then collide producing new particles. Each proton in the beams has a kinetic energy of 2.0 GeV.

Explain why new particles are formed.
What is the maximum net mass of the new particles created per collision? (15)

What is the advantage of using circular particle accelerators in particle physics? (6)

(mass of alpha particle = 6.6447×10^{-27} kg; mass of proton = 1.6726×10^{-27} kg;
mass of lithium nucleus = 1.1646×10^{-26} kg; speed of light = 2.9979×10^{8} m s^{-1};
charge on electron = 1.6022×10^{-19} C)

Question 7

(*j*) A kaon consists of a strange quark and an up anti-quark.
What type of hadron is a kaon? (7)

Question 8

(*a*) Baryons and mesons are made up of quarks and experience the four fundamental forces of nature.

List the four fundamental forces and state the range of each one. (8)

Name the three positively charged quarks.
What is the difference in the quark composition of a baryon and a meson?
What is the quark composition of the proton? (12)

In a circular accelerator, two protons, each with a kinetic energy of 1 GeV, travelling in opposite directions, collide.
After the collision two protons and three pions are emitted.
What is the net charge of the three pions? Justify your answer. (9)
Calculate:

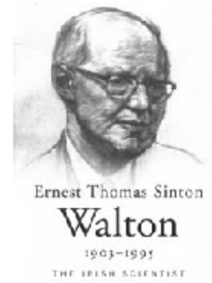
(i) the combined kinetic energy of the particles after the collision;

(ii) the maximum number of pions that could have been created during the collision. (24)

(charge on electron = 1.6022×10^{-19} C; mass of proton = 1.6726×10^{-27} kg; mass of pion = 2.4842×10^{-28} kg; speed of light = 2.9979×10^{8} m s^{-1})

Question 9

(a) Read the following passage and answer the accompanying questions.



Ernest Walton was one of the legendary pioneers who made 1932 the *annus mirabilis* of experimental nuclear physics. In that year James Chadwick discovered the neutron; Carl Anderson discovered the positron; Fermi articulated his theory of radioactive decay; and Ernest Walton and John Cockcroft split the nucleus by artificial means. In their pioneering experiment Cockcroft and Walton bombarded lithium nuclei with high-energy protons linearly accelerated across a high potential difference (*c.* 700 kV). The subsequent disintegration of each lithium nucleus yielded two helium nuclei and energy. Their work gained them the Nobel Prize in 1951.

(Adapted from "Ernest Thomas Sinton Walton 1903 –1995 The Irish Scientist" McBrierty; 2003)

(i) Draw a labelled diagram to show how Cockcroft and Walton accelerated the protons. (6)

What is the velocity of a proton when it is accelerated from rest through a potential difference of 700 kV? (12)

Write a nuclear equation to represent the disintegration of a lithium nucleus when bombarded with a proton. (9)

Calculate the energy released in this disintegration. (12)

(ii) Compare the properties of an electron with that of a positron. (5)

What happens when an electron meets a positron? (3)

(iii) In beta decay it appeared that momentum was not conserved.

How did Fermi's theory of radioactive decay resolve this? (9)

(charge on electron = 1.6022×10^{-19} C; mass of proton = 1.6726×10^{-27} kg;
mass of lithium nucleus = 1.1646×10^{-26} kg; mass of helium nucleus = 6.6443×10^{-27} kg;
speed of light = 2.9979×10^{8} m s^{-1})

Question 10

1. In investigating the relationship between the period and the length of a simple pendulum, a pendulum was set up so that it could swing freely about a fixed point. The length l of the pendulum and the time t taken for 25 oscillations were recorded. This procedure was repeated for different values of the length.

The table shows the recorded data.

l/cm	40.0	50.0	60.0	70.0	80.0	90.0	100.0
t/s	31.3	35.4	39.1	43.0	45.5	48.2	50.1

The pendulum used consisted of a small heavy bob attached to a length of inextensible string. Explain

(i) why a small heavy bob was used;
(ii) why the string was inextensible. (9)

Describe how the pendulum was set up so that it swung freely about a fixed point. Give one other precaution taken when allowing the pendulum to swing. (7)

Draw a suitable graph to investigate the relationship between the period of the simple pendulum and its length. What is this relationship? Justify your answer. (24)

Question 11

(a) During a nuclear interaction an antiproton collides with a proton. Pair annihilation takes place and two gamma ray photons of the same frequency are produced.

What is a photon? Calculate the frequency of a photon produced during the interaction.(12)

Why are two photons produced? Describe the motion of the photons after the interaction. (9)

How is charge conserved during this interaction? (6)

After the annihilation, pairs of negative and positive pions are produced. Explain why. (6)

Pions are mesons that consist of up and down quarks and their antiquarks. Give the quark composition of (i) a positive pion, (ii) a negative pion. (9)

List the fundamental forces of nature that pions experience. (6)

A neutral pion is unstable with a decay constant of 2.5×10^{12} s^{-1}. What is the half-life of a neutral pion? (8)

(mass of proton= 1.673×10^{-27} kg; Planck constant = 6.626×10^{-34} J s;
speed of light = 2.998×10^{8} m s^{-1})

Question 12

(*j*) The existence of the neutrino was proposed in 1930 but it was not detected until 1956. Give two reasons why it is difficult to detect a neutrino. (7)