Question 1

first experimental verification of $E = mc^2$ / first transmutation using artificially accelerated particles / first artificial splitting of a nucleus / development of linear accelerator *(any two)* **(4 + 3)**

Describe how a galvanometer may be converted into a voltmeter.

connect a large resistor / multiplier **(4)**

in series **(3)**

Question 2

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

gravitational, weak (nuclear) and electromagnetic **(3 × 2)**

in correct order **(1)**

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

$e^- + e^+$ // $2m_ec^2$ **(4)**

$\rightarrow 2hf$ / 2γ // $= 2hf$ **(3)**

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

$hf = mc^2$ **(4)**

1.2356×10^{20} Hz *(–1 for omission of or incorrect units)* **(3)**

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

momentum **(4)**

is conserved **(3)**

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

$^{11}_{6}C \rightarrow {}^{11}_{5}B + {}^{0}_{1}e \; (+\nu_e)$ *(–3 for extra particles)* **(7 × 1)**

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

$\lambda = \ln 2 / T_{½}$ **(4)**

0.000578 s^{-1} *(–1 for omission of or incorrect units)* **(3)**

(*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.

short half-life / too many would have decayed before they could be used **(7)**

(*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.

qrB *(centripetal force = magnetic force for 4 marks)* **(7)**

(qvB or mv^2/r or $mr\omega^2$ for 4 marks)

(–1 if "e" is used in place of "q")

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?

high voltage / large electric field — 6

How did they detect the alpha-particles?

scintillations / flashes of light / fluorescence — 3
when particles hit (zinc sulfide) screen — 3

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

$^{7}_{3}Li + ^{1}_{1}H \rightarrow ^{4}_{2}He + ^{4}_{2}He$ — 9

(–1 for each incorrect or omitted symbol or number)

1st experimental verification of $E = mc^2$ / first artificial splitting of the nucleus (atom) / first transmutation using artificially accelerated particles / awarded Nobel Prize — 3

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

700 keV = 1.12×10^{-13} J — 3
$E = ½mv^2$ — 3
correct substitution — 3
$v = 1.16 \times 10^{7}$ m s^{-1} *(–1 for omission of or incorrect units)* — 3

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?

so that particles do not collide with gas particles // to increase mean free path — 3

What is the purpose of accelerating the particles to high velocities?

to overcome repulsive forces // to create new matter — 4

What is the purpose of the magnets?

to contain the particles (in a circular path) *(stated or implied)* — 4

Give an advantage of a circular accelerator over a linear accelerator.

takes up less space // particles can achieve greater <u>energy</u> / <u>speed</u> — 3

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

no — 3
neutrons have no charge and are therefore not affected by <u>electric</u> / <u>magnetic</u> fields — 3

Question 4

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

an electron with + charge / electron antiparticle / ${}^{0}_{+1}e$ — 6

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

$${}^{0}_{-1}e + {}^{0}_{+1}e \rightarrow \gamma + \gamma \quad / \quad e^{+} + e^{-} \rightarrow 2\gamma$$ — 6

(iii) **Why are photons produced in this interaction?**

mass converted into energy — 3

Explain why two photons are produced.

to conserve momentum — 3

Calculate the minimum frequency *f* of the photons produced.

mass of electron = $9.1093826 \times 10^{-31}$ kg — 3

$E = mc^2$ — 3

$E = (9.1093826 \times 10^{-31})(3 \times 10^{8})^2 \quad / \quad E = 8.198444 \times 10^{-14}$ J — 3

$E = hf \;/\; f = \frac{E}{h} \;/\; f = \frac{8.198444 \times 10^{-14}}{6.6260693 \times 10^{-34}}$ — 3

$f = 1.237 \times 10^{20}$ Hz — **(–1 for omission of or incorrect units)** — 3

(–1 for factor of 2 error in answer)

Explain why the photons produced usually have a greater *f* than your calculated minimum *f* value.

(in addition to rest mass) the colliding particles have kinetic energy — 3

(iv) **Why must two positrons travel at high speeds so as to collide with each other?**

to overcome force of repulsion — 6

How are charged particles given high speeds?

particle accelerators / linear accelerator / cyclotron /synchrotron/magnetic fields/electric fields — 6

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

(in conflict with) conservation of charge or equivalent statement — 8

(‘zero charge after interaction’ …. award 4 marks)

Question 5

(a)

(i) What is anti-matter?

material/matter/particle that has same mass as another particle — 3

(but equal in magnitude and) opposite charge — 3

An anti-matter particle was first discovered during the study of cosmic rays in 1932. Name the anti-particle and give its symbol.

positron / anti-electron — 3

e^{+} / β^{+} / $\overline{e}$ — 3

What happens when a particle meets its anti-particle?

(entire) mass converted to / pair annihilation occurs (followed by creation of) — 3

energy / photon(s) — 3

18

(ii) What is meant by pair production?

particle and (its) antiparticle created — 3

from energy / gamma rays — 3

(the production of a positron and an electron from a gamma ray photon … 6 marks)

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.

For photon: $E = hf$ / $E = \left(6.6\times10^{-34}\right)\left[3.6\times10^{20}\right]$ / 2.376×10^{-13} (J) — 3

$E = mc^2$ / $E = 2mc^2$ — 3

$E = 2\left(9.1\times10^{-31}\right)\left(3.0\times10^{8}\right)^2$ / $=1.638\times10^{-13}$ (J) — 3

$\Delta E = [2.376 - 1.638]10^{-13}$ / 7.38×10^{-14} — 3

E_k per particle $= 3.69\times10^{-14}$ J — 3

(–1 for omission of or incorrect units) — **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.

composition	charge	name
$u + \overline{u}$	$\Rightarrow 0$	$\Rightarrow \pi^0$ / pi−neutral
$u + \overline{d}$	$\Rightarrow +1$	$\Rightarrow \pi^+$ / pi−plus
$d + \overline{u}$	$\Rightarrow -1$	$\Rightarrow \pi^-$ / pi−minus
$d + \overline{d}$	$\Rightarrow 0$	$\Rightarrow \pi^0$ / pi−neutral

composition — 4 × 1

charge — 4 × 1

name — 4 × 1

(award 4 marks for collective name '*pions*')

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

(James) Joyce — 5

Question 6

Question 10 (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?

high voltage 4
scintillations / flashes of light / zinc sulphide (or phosphor) screen 4

8

Write a nuclear equation to represent the splitting of a lithium nucleus by a proton.

$^{7}_{3}Li + ^{1}_{1}H \rightarrow ^{4}_{2}He + ^{4}_{2}He$ **(1 mark per each correct component)** 4×3

Calculate the energy released in this reaction.

loss in mass = $\underline{(1.33186\times 10^{-26}) - (1.32894\times 10^{-26})}$ / $\underline{2.92\times 10^{-29}}$ 3
$E = mc^2$ 3
$E = \underline{(2.92\times 10^{-29})(2.9979\times 10^{8})^2\ J}$ / $\underline{2.6\times 10^{-12}\ J}$ 3
(–1 for omission of or incorrect unit)

21

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

atom mostly empty space 3
protons did not collide with lithium nucleus / passed straight through 3

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.

kinetic energy of protons // energy converted 3
changed into mass // into mass 3
[e.g. 'mass/energy conservation' ... 2 × 3]

6

What is the maximum net mass of the new particles created per collision?

total energy = 4 GeV **(–1 if only 2 GeV used in calculations)** 3

$m = \frac{E}{c^2}$ // $m = \frac{(4\times 10^{9})(1.6\times 10^{-19})}{(2.9979\times 10^{8})^2}$ // $m = \frac{6.4\times 10^{-10}}{8.9874\times 10^{16}}$ 3

$m = 7.121\times 10^{-27}$ kg **(–1 for omission of or incorrect unit)** 3

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

take up less space // greater (particle) speeds / energy 6

15

Question 7

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

a meson 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.**

strong (nuclear) --- short (range) (10^{-15} m) 1+1
weak (nuclear) --- short (range) (10^{-18} m) 1+1
gravitational --- infinite (range) / $\propto \frac{1}{d^2}$ 1+1
electromagnetic --- infinite (range) / $\propto \frac{1}{d^2}$ 1+1

Name the three positively charged quarks.

up, top, charm / u, t, c 2+2+2

What is the difference in the quark composition of a baryon and a meson?

(baryon): three quarks 3
(meson): one quark and one antiquark 3

What is the quark composition of the proton?

up, up, down **(−1 per incorrect item)** 3

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.

zero 6
(electric) charge is conserved 3

Calculate:

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

(energy equivalent of a pion:) $E = mc^2$ 3

$E = (2.4842\times10^{-28})(2.9979\times10^{8})^2$ 3

$E = 2.2327\times10^{-11}$ J 3

$E = 1.3935\times10^{8}$ eV 3

(for 3 pions :) $E = 6.6980\times10^{-11}$ J / 4.18047×10^{8} eV 3

energy after collision $= (2\times10^{9}) - (4.18047\times10^{8})$ / 1.58195×10^{9} eV / 2.535×10^{-10} J 3

(−1 for omission of or incorrect units)

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

number of pions $= \frac{1.581953\times10^{9}}{1.3935\times10^{8}}$ / $11.3524 \Rightarrow 11$ pions 3

$\Rightarrow$ maximum number of pions = 3 + 11 / 14 pions 3

(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

Question 10 (a) **Answer either part *(a)* or part *(b)*.**

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.

anode and cathode (in tube) / (lithium) target / two helium nuclei — 3

p.d / V / H.T — 3

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

$W = qV$ — 3

$W = \frac{1}{2}mv^2$ — 3

$$v^2 = \frac{2(1.6022 \times 10^{-19})(7.00 \times 10^5)}{1.6726 \times 10^{-27}}$$ — 3

$\Rightarrow v = 1.16 \times 10^7 \text{ m s}^{-1}$ **(-1 for omission of or incorrect units)** — 3

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

$^7_3Li + ^1_1H \rightarrow 2\,^4_2He$ **(accept *p* for *H* and *α* for *He* ; -1 for each error)** — 3 x 3

Calculate the energy released in this disintegration.

mass of reactants = $1.1646 \times 10^{-26} + 1.6726 \times 10^{-27}$ or 1.33186×10^{-26} (kg) — 3

mass of products = $2(6.6443 \times 10^{-27})$ or 1.32886×10^{-26} (kg) — 3

$\Delta m = 3.00 \times 10^{-29}$ kg — 3

$E = mc^2$ or $E = (3.00 \times 10^{-29})(9 \times 10^{16})$ or $E = 2.7 \times 10^{-12}$ J — 3

(-1 for omission of or incorrect units)

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

(both have) equal mass / charges equal / charges opposite (in sign) / matter and anti-matter

any *one* direct comparison — 5

What happens when an electron meets a positron?

(pair) annihilation / energy released(or produced) / γ-rays emitted — 3

(iii) In beta decay it appeared that momentum was not conserved.
How did Fermi's theory of radioactive decay resolve this?

any reference to *neutrino* — 6

(neutrino had the *missing*) momentum — 3

(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

Question 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)

small heavy bob: to reduce air resistance/friction // to keep string taut 3
string inextensible: so that length remains constant/fixed 6

{"So that formula is applicable to system/arrangement/apparatus" // "so that motion is SHM" // "to limit the number of variables to two" … (3)}

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)

string placed between two coins/a split cork 4

small angle/no draughts /one plane only / avoid spinning 3

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)

T/s	1.25	1.42	1.56	1.72	1.82	1.93	2.00
T^2/s^2	1.57	2.01	2.45	2.96	3.31	3.72	4.02
$\sqrt{l}$/m$^{1/2}$	0.63	0.71	0.77	0.84	0.89	0.95	1.00

values of t divided by 25 (to get T) 3
axes correctly labelled (T^2 vs. l or T vs. $\sqrt{l}$) 3
at least six points plotted correctly **(-1 for each incorrect point plotted)** 2 x 3
straight line drawn **(consistent with plotted points)** 3
good distribution (about straight line) 3
T^2 proportional to l / $T \propto \sqrt{l}$ **(valid conclusion from graph required)** 3
straight line through the origin 3

[t^2 vs. l …. .. max. (6 x 3)]

Question 11

Question 10 (a)

[Answer part *(a)* or part *(b)*.]

(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)

packet /bundle /quantum of (*electromagnetic* or *light*) energy /radiation 3

m [= mass of proton + mass of antiproton] = $2(1.673 \times 10^{-27})$ / 3.346×10^{-27} kg 3

$E = mc^2$ / $(3.346 \times 10^{-27})(2.998 \times 10^{8})^2$ / 3.0074×10^{-10} 3

(for one photon:) $f = E/h$ / $\{1.5037 \times 10^{-10} / 6.626 \times 10^{-34}\}$ / 2.2694×10^{23} Hz 3

{ -1 for omission of or incorrect unit. Also, –1 if final answer is given as $2(2.2694 \times 10^{23}) = 4.545 \times 10^{23}$ Hz }

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

so that momentum is conserved / so that momt. before = momt. after 6
they travel in opposite directions 3

How is charge conserved during this interaction? (6)
(total) charge before = +1-1 = 0 3
(total) charge after = 0 since photons have zero charge 3

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

energy (of photons) is converted into matter / pair production occurs / to conserve charge 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)

any quark , antiquark pair 3
π^+ => up and anti-down / $u\bar{d}$ 3
π^- => down and anti-up / $d\bar{u}$ 3

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

electromagnetic, strong (nuclear), weak (nuclear), gravitational (any order) 2+2+1+1

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)

$\lambda T_{1/2} = \ln 2$ [= 0.693] 3

$T_{1/2} = 0.693 / 2.5 \times 10^{12}$ 3

$T_{1/2} = 2.772 \times 10^{-13}$ s [≈ 2.8×10^{-13} s] (-1 for omission of or incorrect unit) 2

(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.**

uncharged /very small (mass) /zero mass / interact weakly with matter (any two) 4+3