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EDEXCEL A LEVEL PHYSICS: QUESTIONS BY TOPIC

Nuclear and Particle Physics (8)

A Level Physics Topic 8

42 questions · 294 marks · Mark schemes included

A Level only content · Pearson Edexcel 8PH0 / 9PH0 papers, 2016–2025

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HOW TO USE THIS BOOKLET

Questions are grouped by specification sub-topic and run from the lowest mark tariff to the highest within each one.

Click any row below to jump straight to that sub-topic or question.

On every question page, click ANSWER in the top-right corner to jump to its mark scheme.

Diagrams, graphs, tables and data are printed exactly as they appeared in the original papers.

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QUESTIONS

42 questions · 294 marks · 3 sub-topics



SUB-TOPIC 8.1

ATOMIC STRUCTURE AND ALPHA PARTICLE SCATTERING

Sub-topic 8.1 · 13 questions · 62 marks · lowest tariff first



8 The alpha particle scattering experiment led to a number of observations and conclusions.

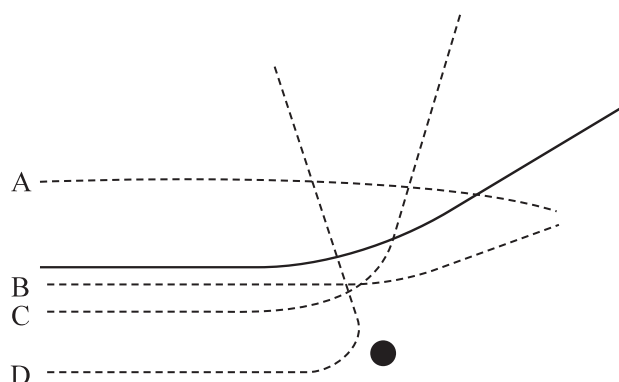
Which row in the table gives a correct observation and corresponding conclusion from the alpha particle scattering experiment?

	Observation	Conclusion
☒ A	Most alpha particles come straight back.	The nucleus is charged.
☒ B	Most alpha particles come straight back.	The atom is mainly empty space.
☒ C	Most alpha particles go straight through.	The atom is mainly empty space.
☒ D	Most alpha particles go straight through.	The nucleus is charged.

(Total for Question 8 = 1 mark)



10 The solid line shows the path of an alpha particle as it passes close to a nucleus.



Another alpha particle approaches the nucleus with the same initial kinetic energy.

Which dashed path is possible for this alpha particle?

- ☒ A
- ☒ B
- ☒ C
- ☒ D

(Total for Question 10 = 1 mark)

Questions 9 and 10 refer to the information below.

Alpha particle scattering investigations were first carried out in the early part of the 20th century.

- 9 An alpha particle with initial kinetic energy $8.8 \times 10^{-13} \text{ J}$ approaches a nucleus of a gold ($^{197}_{79}\text{Au}$) atom.

Which of the following is an equation for the closest distance r , in metres, between the alpha particle and the nucleus?

☐ A $r = 8.99 \times 10^9 \left(\frac{2 \times 1.6 \times 10^{-19} \times 79 \times 1.6 \times 10^{-19}}{8.8 \times 10^{-13}} \right)$

☐ B $r = \frac{2 \times 1.6 \times 10^{-19} \times 197 \times 1.6 \times 10^{-19}}{8.99 \times 10^9 \times 8.8 \times 10^{-13}}$

☐ C $r = 8.99 \times 10^9 \left(\frac{8.8 \times 10^{-13}}{4 \times 1.6 \times 10^{-19} \times 79 \times 1.6 \times 10^{-19}} \right)$

☐ D $r = 8.99 \times 10^9 \left(\frac{2 \times 79}{8.8 \times 10^{-13}} \right)$

(Total for Question 9 = 1 mark)



Questions 9 and 10 refer to the information below.

Alpha particle scattering investigations were first carried out in the early part of the 20th century.

10 Which of the following conclusions could **not** be made as a result of these investigations?

- ☐ **A** The atom is mostly empty space.
- ☐ **B** The atom is neutral.
- ☐ **C** The nucleus is charged.
- ☐ **D** The nucleus is very small compared to the atom.

(Total for Question 10 = 1 mark)



1 One isotope of oxygen is $^{17}_8\text{O}$.

Which row of the table shows the number of neutrons and the number of protons in a nucleus of $^{17}_8\text{O}$?

	Number of neutrons	Number of protons
☐ A	8	9
☐ B	8	17
☐ C	9	8
☐ D	17	8

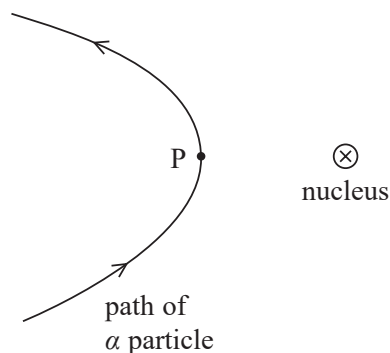
(Total for Question 1 = 1 mark)



Questions 8 and 9 refer to the information below.

Alpha particle scattering investigations were first carried out in the early part of the 20th century.

The diagram shows the path of an α particle that is being deflected by the nucleus of a gold atom. The closest distance of approach of the α particle to the nucleus is at point P.



- 8 Which row in the table describes the speed and potential energy of the α particle at point P on this path?

	Speed at P	Potential energy at P
☒ A	greatest	greatest
☒ B	greatest	least
☒ C	least	greatest
☒ D	least	least

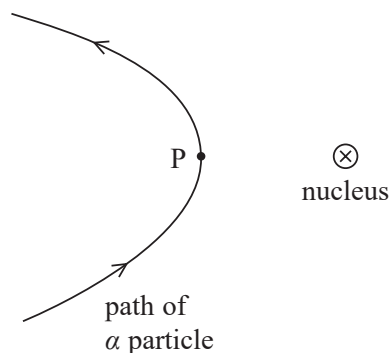
(Total for Question 8 = 1 mark)



Questions 8 and 9 refer to the information below.

Alpha particle scattering investigations were first carried out in the early part of the 20th century.

The diagram shows the path of an α particle that is being deflected by the nucleus of a gold atom. The closest distance of approach of the α particle to the nucleus is at point P.



9 Which of the following can be concluded about a gold atom from the deflection of this α particle?

- ☐ A The atom contains electrons.
- ☐ B The atom has zero charge.
- ☐ C The nucleus is very small compared to the atom.
- ☐ D The nucleus of the atom is positively charged.

(Total for Question 9 = 1 mark)

1 Which of the following was investigated by the large-angle alpha particle scattering experiment?

- ☐ A structure of an atom
- ☐ B structure of a nucleon
- ☐ C structure of a nucleus
- ☐ D structure of a quark

(Total for Question 1 = 1 mark)



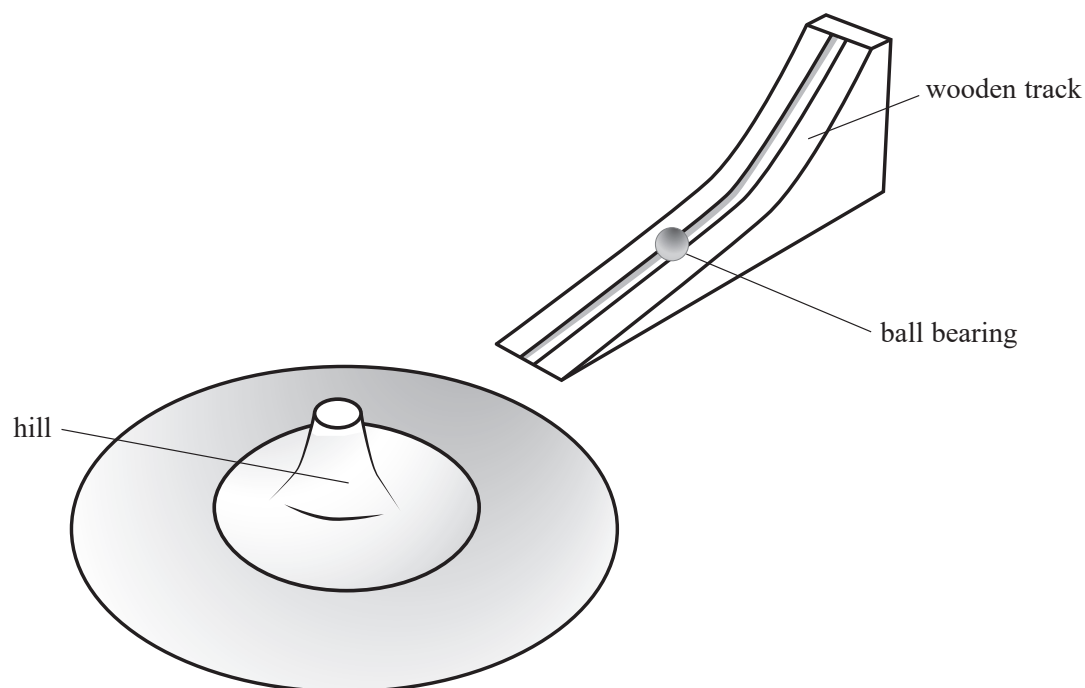
*4 Alpha particle scattering experiments led Rutherford to propose the nuclear model of the atom. Alpha particles were directed towards a thin gold foil.

Describe how evidence from these experiments supports the nuclear model of the atom.

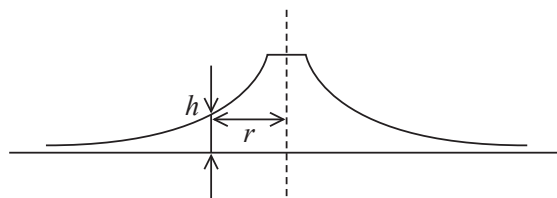
(Total for Question 4 = 6 marks)



- 14 The diagram shows a model used to demonstrate alpha particle scattering. A ball bearing is set rolling on a wooden track. The track is positioned so that the ball bearing rolls onto a metal sheet with a curved surface known as a 'hill'.



The diagram shows a vertical cross-section through the hill. The surface is curved so that the height of a point h on the curved surface is inversely proportional to the distance r from the centre of the hill.



- (a) Explain why the hill is suitable as a model for the electric field surrounding the nucleus of an atom.

(3)

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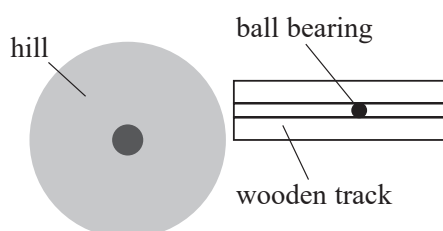
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- (b) A plan view of the arrangement is shown.



The wooden track is moved to different positions and the ball bearing is released.

Describe the results of the alpha particle scattering experiment and how these can be demonstrated by moving the wooden track to different positions.

(4)

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(Total for Question 14 = 7 marks)



15 At the beginning of the 20th century, Rutherford carried out large-angle alpha particle scattering experiments using gold ($^{197}_{79}\text{Au}$) foil.

The vast majority of the alpha particles went straight through the foil whilst a few were deflected straight back.

(a) Describe how the model of the atom changed, as a consequence of these experiments.

(4)

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(b) In one experiment the alpha particles had an initial energy of 7.7 MeV.

Calculate the distance of closest approach of the alpha particles to the nucleus of a gold atom. Assume that the gold nucleus remains at rest.

(4)

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Distance of closest approach = ...



- (c) Rutherford also carried out the experiment with aluminium ($^{27}_{13}\text{Al}$) foil.
The aluminium foil had the same thickness as the gold foil and the alpha particles had the same initial kinetic energy.

The following observations were made.

Observation 1:

The fraction of alpha particles scattered at any particular angle for aluminium foil was always much less than for gold foil.

Observation 2:

The alpha particles scattered from aluminium foil had less kinetic energy than the alpha particles scattered from gold foil.

Explain how these observations can be used to deduce how an aluminium nucleus compares to a gold nucleus.

(4)

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(Total for Question 15 = 12 marks)



17 Over one hundred years ago, Rutherford supervised a series of experiments using a source of alpha particles and thin gold foil.

- (a) Describe the model of the atom that Rutherford proposed as a result of this series of experiments.

(3)

- (b) The initial kinetic energy of an alpha (${}^4_2\alpha$) particle is 7.3×10^{-13} J.

- (i) In a textbook, it states that an alpha particle with this energy would be brought to rest when it reached a distance of 5.0×10^{-14} m from the centre of the gold nucleus (${}^{197}_{79}\text{Au}$).

Deduce whether this statement is correct.

(4)



(ii) Determine the initial momentum of the alpha particle.

(3)

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Initial momentum = ...

(c) An alpha particle moves along a path directly towards a gold nucleus, as shown.



(i) An elastic interaction occurs and the alpha particle recoils.

State what is meant by an elastic interaction.

(1)

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(ii) State what happens to the atoms in the gold foil as a result of these interactions.

(1)

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(Total for Question 17 = 12 marks)



12 Our understanding of the atom has developed over time, from early models in which atoms were considered to be hard incompressible spheres, through to the nuclear model of the atom and the ladder model in which electrons exist in a discrete number of allowed energy states.

*(a) The model of atoms as hard incompressible spheres, moving rapidly and randomly, can be used to explain why gases exert a pressure.

Explain, using ideas of momentum, why the pressure exerted by a gas increases as the temperature of the gas increases.

(6)

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(b) The nuclear model of the atom was established following a series of experiments in which alpha particles were directed at thin gold foil.

- (i) An alpha particle approaching a gold nucleus, ${}^{197}_{79}\text{Au}$, head-on will be brought to rest and returned along its original path.

Calculate the minimum distance between the alpha particle and the nucleus for alpha particles of energy of 5.5 MeV.

(4)

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Minimum distance = ...

- (ii) It is observed that electrons, with energy of 5.5 keV, are diffracted as they pass through the thin gold foil.

Explain a conclusion about the electrons that can be made from this observation.

(3)

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- (c) In the energy ladder model of the atom, electrons exist in a discrete number of allowed energy states. The collision of electrons with gold atoms may lead to the production of high frequency electromagnetic radiation.

Explain how high frequency electromagnetic radiation may be produced when electrons collide with atoms in a metal.

(4)

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(Total for Question 12 = 17 marks)

SUB-TOPIC 8.2

PARTICLE ACCELERATORS AND DETECTORS

Sub-topic 8.2 · 10 questions · 86 marks · lowest tariff first



9 Electric and magnetic fields can be used in particle accelerators.

Which row in the table correctly describes the use of electric and magnetic fields in the particle accelerator indicated?

	Particle accelerator	Magnetic field	Electric field
☒ A	cyclotron	not used	used to accelerate particles
☒ B	cyclotron	used to accelerate particles	used to accelerate particles
☒ C	linac	used to accelerate particles	not used
☒ D	linac	used to accelerate particles	used to accelerate particles

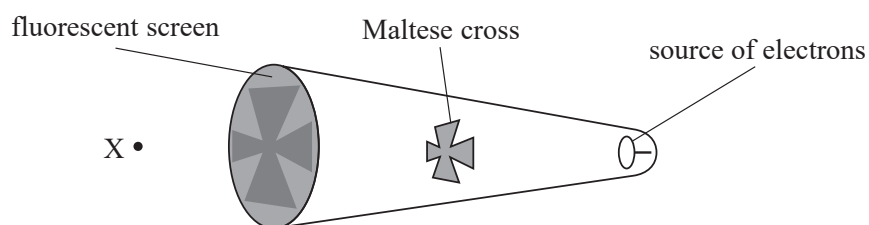
(Total for Question 9 = 1 mark)



Questions 4 and 5 refer to the information below.

A demonstration is carried out using a beam of electrons in an evacuated tube.

When electrons hit a fluorescent screen, light is emitted. A piece of metal, in the shape of a Maltese cross, stops electrons and produces a shadow on the screen as shown.



4 The electrons are produced by heating a metal filament.

Which of the following is the name of this process?

- ☐ **A** ionisation
- ☐ **B** scattering
- ☐ **C** the photoelectric effect
- ☐ **D** thermionic emission

(Total for Question 4 = 1 mark)

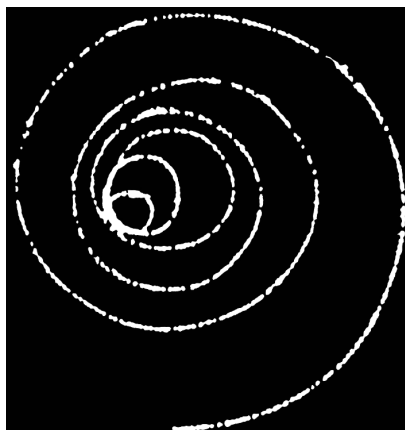
2 Which of the following could **not** be accelerated in a LINAC?

- ☐ A electron
- ☐ B helium atom
- ☐ C proton
- ☐ D uranium ion

(Total for Question 2 = 1 mark)



5 A positron produced a track in a detector, as shown.



(Source: © Science Source/SCIENCE PHOTO LIBRARY)

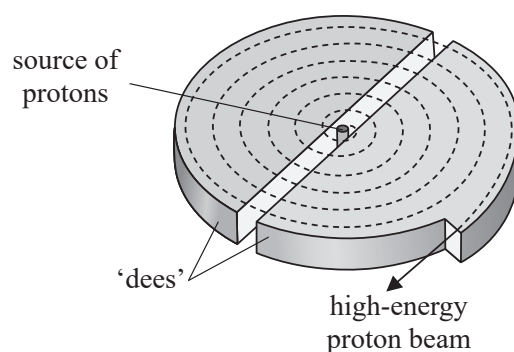
Which of the following is the direction of the magnetic field in this detector?

- ☐ A down the page
- ☐ B into the page
- ☐ C out of the page
- ☐ D up the page

(Total for Question 5 = 1 mark)

13 Proton beam therapy is being introduced in the UK as a new cancer treatment.

A beam of protons is accelerated by a cyclotron to an energy of 23 MeV and is then focused onto a tumour.



*(a) Explain how the cyclotron produces the high-energy proton beam.

(6)

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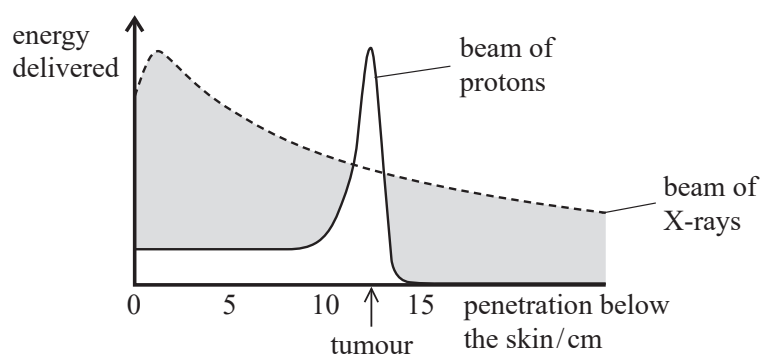
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(b) Conventional treatment may use X-rays to deliver energy to a tumour.

The graph shows the variation of energy delivered with penetration below the skin for a beam of protons and a beam of X-rays.



Deduce why the beam of protons could be a more effective treatment for tumours than a beam of X-rays.

(2)

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(c) Developing new cancer treatments is expensive.

Give two possible reasons why money should be provided for the development of this new cancer treatment.

(2)

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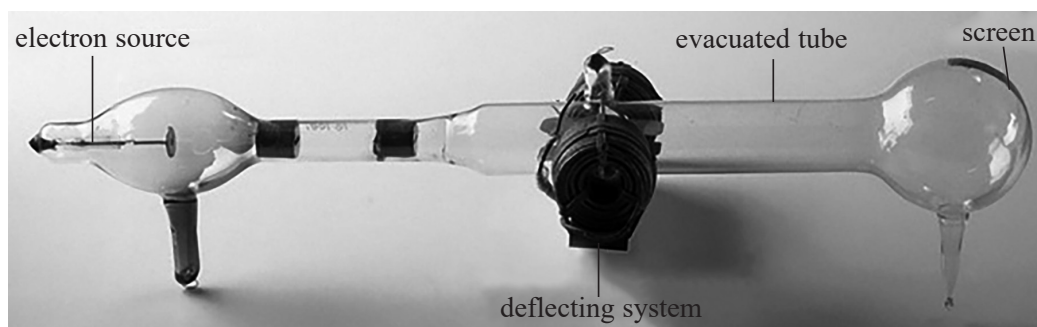
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(Total for Question 13 = 10 marks)

- 7 At the end of the 19th century, J.J. Thompson used electric and magnetic fields to deflect beams of charged particles. A photograph of his apparatus is shown.



© Science Museum London

Electrons were accelerated through a potential difference to produce a beam of high-energy electrons. The beam was then deflected in perpendicular directions by the magnetic and electric fields. The final position of the beam on the screen was determined by the charge and mass of the electrons.

- (a) Explain how electrons from the source become a beam of high-energy electrons.

(2)

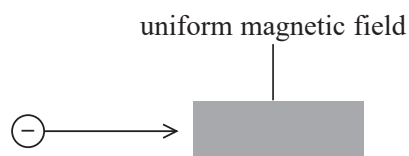
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- (b) An electron is travelling left to right and enters a region of uniform magnetic field as shown below. The direction of the magnetic field is perpendicular to the direction of travel of the electron.



- (i) The magnetic field deflects the electron in the direction up the page.

Explain the direction of the magnetic field that would produce this deflection.

(2)

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- (ii) Explain why the electron would travel in a circular path if no other forces acted on it.

(2)

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- (c) In a modern version of Thompson's experiment, a uniform electric field of electric field strength E is applied so that the electric and magnetic forces on the electrons are equal and in opposite directions.

- (i) Show that for electrons to be undeflected their velocity must be given by

$$v = \frac{E}{B}$$

where B is the magnetic flux density of the magnetic field.

(2)

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- (ii) The beam is produced by accelerating electrons through a potential difference of 250 V. The electric field strength is $1.4 \times 10^4 \text{ V m}^{-1}$. The magnetic flux density is $1.5 \times 10^{-3} \text{ T}$.

Calculate the value of the specific charge e/m for the electron using this data.

(3)

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$e/m =$



- (d) In his original experiments, Thompson determined the specific charge of a range of particles. His results indicated that the specific charge of an electron is about 2000 times bigger than that for a hydrogen ion.

Deduce what conclusion can be made from this information.

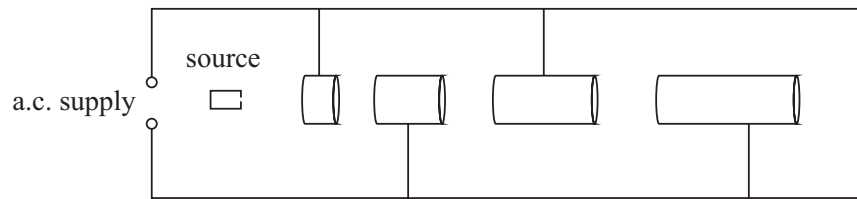
(1)

(Total for Question 7 = 12 marks)



18 At the Facility for Rare Isotope Beams (FRIB) isotopes of elements that do not occur naturally can be produced.

(a) FRIB contains a linear accelerator. The initial section of the accelerator is shown.



Explain why the tubes get progressively longer.

(4)

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(b) A uranium atom ($^{238}_{92}\text{U}$) has 80 electrons removed. The uranium ion is then accelerated between two adjacent tubes until its kinetic energy is 200 MeV per nucleon.

(i) Calculate the accelerating potential difference.

(4)

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Potential difference = ...



- (ii) Show that the uranium ions will reach a velocity of about 65% of the speed of light.

(3)

- (c) When a uranium ion hits a target at this speed the ion is likely to break up and produce smaller elements. One particular isotope produced in this way is ${}^{40}_{12}\text{Mg}$. The naturally occurring common stable isotope of magnesium is ${}^{24}_{12}\text{Mg}$.

Explain why the break-up of ${}^{238}_{92}\text{U}$ is likely to produce unusual isotopes such as ${}^{40}_{12}\text{Mg}$.

(2)

(Total for Question 18 = 13 marks)



15 A series of experiments was carried out in the 1970s to investigate the structure of protons using the linac at Stanford, USA.

*(a) Explain how an electron is accelerated in a linac.

(6)

(b) The electron leaves the accelerator with a high energy.

Explain why electrons need high energies to investigate the structure of a proton.

(2)



(c) An electron leaves the accelerator with a momentum of $20 \text{ GeV}/c$.

- (i) Explain, with reference to base units, why GeV/c can be used as a unit of momentum.

(2)

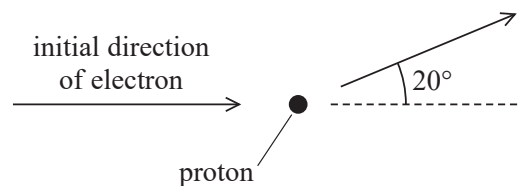
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- (ii) An electron with initial momentum $20 \text{ GeV}/c$ collides with a stationary proton. After the collision the electron is deflected by an angle of 20° as shown and its momentum is $9.1 \text{ GeV}/c$. The momentum of the proton after the collision is $11.9 \text{ GeV}/c$.



Deduce whether the law of conservation of momentum is obeyed.

(3)

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- (iii) The collisions between electrons and the protons in these experiments are sometimes inelastic.

State what is meant by an inelastic collision.

(1)

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(Total for Question 15 = 14 marks)

11 Particle accelerators produce beams of high speed charged particles which are used to investigate particle collisions. New particles are created during the collisions.

(a) In the Large Hadron Collider (LHC), protons are maintained in a circular path by the force exerted on the protons due to a magnetic field.

(i) The magnetic flux density required to maintain the protons in a circular path increases as the kinetic energy of the protons increases.

Explain why.

(2)

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(ii) Calculate the magnetic flux density required to maintain the protons in the LHC when the protons are travelling at a speed of $3.0 \times 10^7 \text{ m s}^{-1}$.

circumference of LHC = 27 km

(4)

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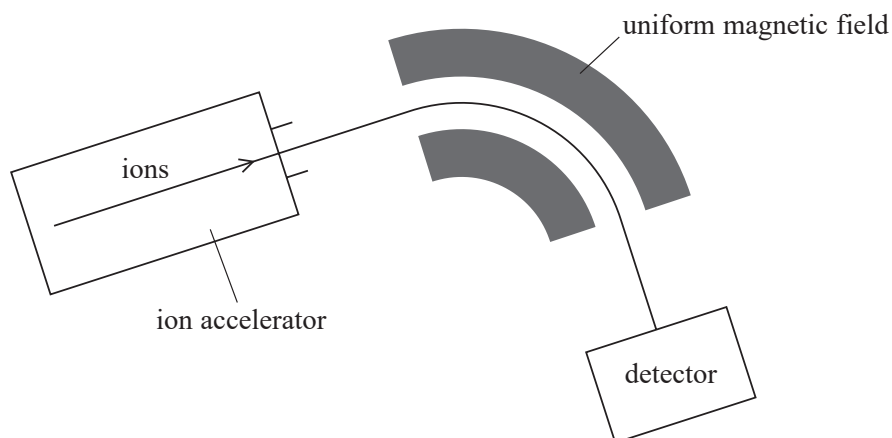
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Magnetic flux density = ...



13 Mass spectrometry is a technique used to separate ions based on their charge to mass ratio.

The atoms in a sample are ionised and then accelerated and formed into a fine beam. This beam is passed into a region of uniform magnetic field and the ions are deflected by different amounts according to their mass.



Analysis of mass spectrometer data shows that chlorine exists in nature as two isotopes, chlorine-35 and chlorine-37.

(a) State what is meant by isotopes.

(1)

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(b) In a mass spectrometer, chlorine-35 ions are accelerated through a potential difference of 8.50 kV to produce an ion beam.

Show that the speed of singly ionised chlorine-35 atoms is about $2.2 \times 10^5 \text{ m s}^{-1}$.

mass of an ion of chlorine-35 = 34.97 u

(4)

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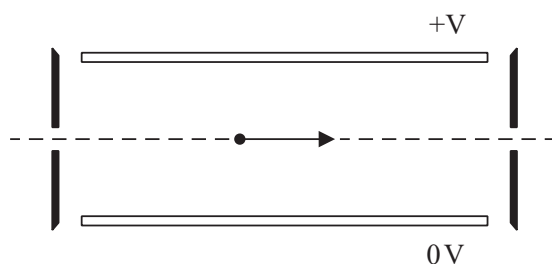
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- (c) In most mass spectrometers the ions are passed through a velocity selector, after being accelerated, to produce a beam of ions of a particular velocity. The velocity selector consists of a pair of parallel plates, across which a potential difference (p.d.) is applied to create an electric field.



In one mass spectrometer the plates are 2.5 cm apart and a p.d. of 135 V is applied.

A magnetic field is also applied to produce a force on the ions in the opposite direction to the force from the electric field. For one particular speed the ions travel in a straight line and emerge from the selector.

- (i) Add to the diagram to indicate the directions of the electric field and the magnetic field. (2)
- (ii) The magnetic flux density applied to the velocity selector is 24.5 mT.

Deduce whether this magnetic flux density is suitable to produce a beam of chlorine-35 ions of speed $2.2 \times 10^5 \text{ m s}^{-1}$. (4)

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(d) After passing through the velocity selector the ion beam enters a region of uniform magnetic flux density 0.35 T with the ions travelling at right angles to the field direction.

(i) Explain why the ions travel in a circular path.

(2)

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(ii) Calculate the radius of the circular path.

(2)

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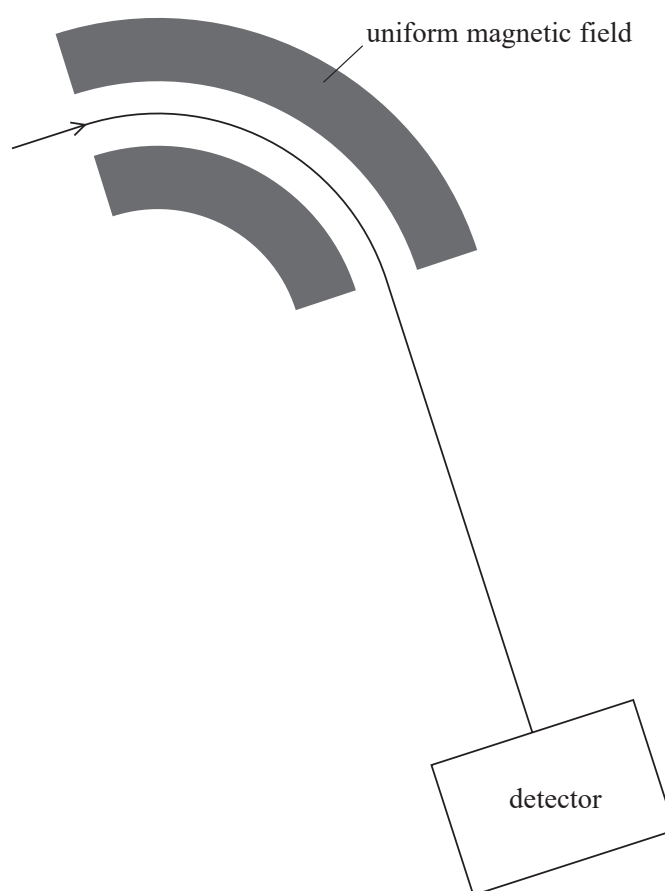
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Radius = ...



- (iii) The diagram shows the path of the chlorine-35 ions in the field. Chlorine-37 ions enter the magnetic field with the same velocity.



1. Add another line to the diagram to show the path of these chlorine-37 ions.

(1)

2. Explain any differences in the paths.

(2)

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(Total for Question 13 = 18 marks)

SUB-TOPIC 8.3

THE STANDARD MODEL, CONSERVATION LAWS AND MASS-ENERGY

Sub-topic 8.3 · 19 questions · 146 marks · lowest tariff first



10 Which of the following particle equations is correct for the decay of a proton within a nucleus?

☐ **A** $p \rightarrow n + \beta^+$

☐ **B** $p \rightarrow p + \beta^+$

☐ **C** $p \rightarrow n + \beta^+ + \nu$

☐ **D** $p \rightarrow p + \beta^+ + \nu$

(Total for Question 10 = 1 mark)



1 Which of the following particles is an example of a fundamental particle?

- ☐ A nucleus
- ☐ B neutrino
- ☐ C pion
- ☐ D proton

(Total for Question 1 = 1 mark)



2 Which row of the table summarises the mass and charge of an antineutron?

	Mass / u	Charge / e
☐ A	0	0
☐ B	0	-1
☐ C	1	0
☐ D	1	+1

(Total for Question 2 = 1 mark)



5 A high-energy proton can interact with a photon to produce two particles.

Which of the following could be the two particles produced?

- ☐ A $n + \pi^0$
- ☐ B $n + \pi^+$
- ☐ C $\pi^0 + \pi^+$
- ☐ D $\pi^- + \pi^+$

(Total for Question 5 = 1 mark)



8 A proton has a mass of 1.67×10^{-27} kg.

Which of the following shows the conversion of this mass to GeV/c^2 ?

☐ A $\frac{1.67 \times 10^{-27} \times 1.60 \times 10^{-10}}{(3.00 \times 10^8)^2}$

☐ B $\frac{1.67 \times 10^{-27} \times 1.60 \times 10^{-19}}{(3.00 \times 10^8)^2}$

☐ C $\frac{1.67 \times 10^{-27} \times (3.00 \times 10^8)^2}{1.60 \times 10^{-10}}$

☐ D $\frac{1.67 \times 10^{-27}}{1.60 \times 10^{-10} \times (3.00 \times 10^8)^2}$

(Total for Question 8 = 1 mark)

2 The π^- particle has a mass of $140 \text{ MeV}/c^2$.

Which row of the table is correct for the antiparticle of a π^- ?

	Particle classification	Mass/ MeV/c^2
☐ A	Baryon	+140
☐ B	Baryon	-140
☐ C	Meson	+140
☐ D	Meson	-140

(Total for Question 2 = 1 mark)



1 A particle has a mass of 1 u and a charge of $-1.6 \times 10^{-19} \text{ C}$.

Which of the following could be the particle?

- ☐ **A** antiproton
- ☐ **B** electron
- ☐ **C** neutron
- ☐ **D** positron

(Total for Question 1 = 1 mark)



2 A subatomic particle consists of the quark combination $u \bar{s}$.

Which of the following is the classification for this particle?

- ☐ A baryon
- ☐ B lepton
- ☐ C meson
- ☐ D nucleon

(Total for Question 2 = 1 mark)



- 4 Muons created in the upper atmosphere can travel towards the Earth's surface at speeds close to the speed of light. Changes to the mass and average lifetime of the muons can then be observed.

Which row of the table describes these changes when muons travel at speeds close to the speed of light?

	Mass	Average lifetime
☒ A	increases	increases
☒ B	increases	decreases
☒ C	decreases	increases
☒ D	decreases	decreases

(Total for Question 4 = 1 mark)

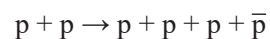


13 Beams of antiprotons are often used in particle physics experiments.

(a) Show that the rest mass of an antiproton is about $900 \text{ MeV}/c^2$.

(4)

(b) Antiprotons can be produced by accelerating and colliding two protons moving in opposite directions. A website suggests a possible outcome for a collision between these protons is described by the nuclear equation:



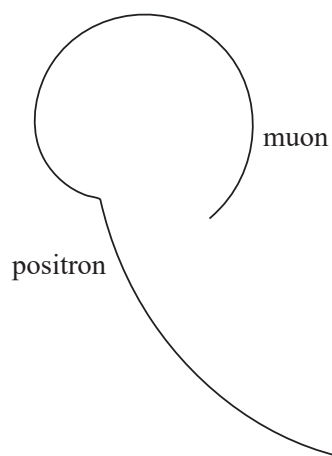
Deduce, by using conservation laws, whether it should be possible to produce an antiproton in this way.

(4)

(Total for Question 13 = 8 marks)



- 14 The decay of a positive muon produced a positron, an electron neutrino and a muon antineutrino. The diagram shows the tracks formed in a particle detector.



- (a) A muon belongs to a family of particles called leptons.

State two features that all particles in the lepton family have in common.

(2)

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- (b) Write a nuclear equation for the decay of the muon (μ) described above.

(2)

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(c) Describe the role of the magnetic field in a particle detector.

(3)

(d) Explain how the diagram gives evidence that a particle or particles, other than the positron, were produced in this decay.

(4)

(Total for Question 14 = 11 marks)



15 A sigma (Σ^+) particle is a baryon. It can decay into a positive pion and a neutron.

- (a) Complete the particle equation for this decay. (2)

$\Sigma^+ \rightarrow$

- (b) Explain whether the conservation laws of charge and baryon number are obeyed for this decay. (2)

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- (c) The table summarises the charges for three types of quark.

Quark	Charge/ <i>e</i>
u	+2/3
d	−1/3
s	−1/3

The sigma particle has one strange quark within its structure.

- Deduce the quark structure for Σ^+ (2)

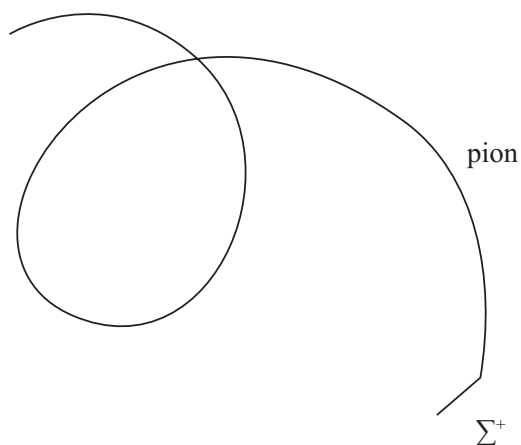
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(d) The diagram shows tracks in a particle detector associated with this decay.



(i) State why the neutron does not leave a track.

(1)

(ii) The initial momentum of the positive pion is $1.1 \times 10^{-19} \text{ N s}$. The scale of the diagram is 1 cm represents 15 cm.

Determine the magnitude of the magnetic flux density acting perpendicularly to the tracks.

(4)

Magnetic flux density = ...

(Total for Question 15 = 11 marks)

17 A cosmic ray, consisting of a fast-moving proton, collides with a proton within the nucleus of an atom in the upper atmosphere. Three particles, a proton, a neutron and a pion result from the collision.

(a) Write a particle equation for this collision.

(2)

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(b) The table shows the properties of two quarks.

Quark	Charge/ e
u	$+2/3$
d	$-1/3$

Give the quark structure for each of the particles produced by this collision.

(3)

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(c) The mass of a pion is $140 \text{ MeV}/c^2$.

Calculate the mass of the pion in kg.

(3)

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Mass = ... kg



- (d) The mass of a neutron is about the same as the mass of a proton. A student suggests that the minimum kinetic energy the cosmic ray proton would need to create the pion in this collision is 140 MeV.

Discuss whether this suggestion is correct. Your answer should include reference to the laws of conservation of momentum and conservation of energy.

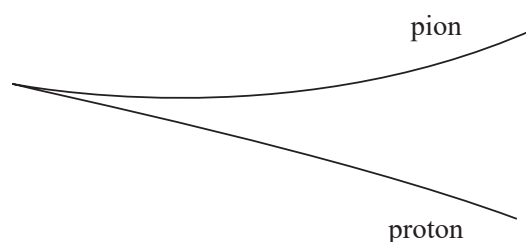
(4)

(Total for Question 17 = 12 marks)



15 A delta particle decays into a proton and a pion.

- (a) The diagram shows tracks in a particle detector formed when the delta particle decays.



- (i) State why it can be concluded from the diagram that the delta particle is neutral.

(1)

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- (ii) Deduce the charge on the pion.

(2)

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- (iii) Complete the particle equation for the decay of the delta (Δ^0) particle.

(1)

$$\Delta^0 \rightarrow$$

- (iv) State why the delta particle must be classified as a baryon based on the evidence of its decay.

(1)

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- (v) Explain how the momentum of the proton compares with the momentum of the pion.

(3)

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- (b) The mass of the delta particle is $1232 \text{ MeV}/c^2$.

- (i) Calculate the mass of the delta particle in kg.

(3)

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Mass = ... kg

- (ii) The mass of the proton is $939 \text{ MeV}/c^2$ and the mass of the pion is $139 \text{ MeV}/c^2$.

Explain why the sum of the masses of the two particles after the decay is not equal to the mass of the delta particle.

(3)

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(Total for Question 15 = 14 marks)



16 The neutral lambda Λ^0 particle is a baryon of mass $1116 \text{ MeV}/c^2$ and contains one strange quark.

(a) The table shows quarks and their relative charge.

Quark	Charge / e
u	$+2/3$
d	$-1/3$
s	$-1/3$

State, with justification, the quark content of a Λ^0 particle.

(2)

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(b) Calculate the mass of the Λ^0 particle in kg.

(3)

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Mass of Λ^0 particle = ... kg

(c) A student suggests five ways a Λ^0 particle might decay. These are

$$\Lambda^0 \rightarrow p + \pi^-$$

$$\Lambda^0 \rightarrow e^+ + e^-$$

$$\Lambda^0 \rightarrow n + \pi^0$$

$$\Lambda^0 \rightarrow n$$

$$\Lambda^0 \rightarrow p + \pi^0$$



Deduce which of these decay processes are **not** possible.

(6)

- (d) Lambda particles were first detected in experiments which made use of cosmic rays entering the atmosphere. Cosmic rays are mainly high-energy protons which have a mass less than that of a lambda particle.

Explain why a cosmic ray could lead to the creation of a lambda particle.

(2)

- (e) The Λ^0 particle cannot be directly observed in particle experiments, however some of the decay products can.

Explain why the Λ^0 particle cannot be directly observed but information about it can be obtained by studying its decay particles.

(3)

(Total for Question 16 = 16 marks)



16 A muon (μ) is a lepton with a mass of $106 \text{ MeV}/c^2$.

(a) Calculate the mass of a muon in kg.

(3)

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Mass of muon = ... kg

(b) Muons are produced from the decay of pions in the upper atmosphere.

An example of this decay is given by the equation

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

(i) Explain how this decay obeys the laws of conservation of charge, baryon number and lepton number.

(3)

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(ii) The masses of these three particles, in MeV/c^2 , are given below.

π^-	μ^-	$\bar{\nu}_\mu$
140	106	≈ 0

Explain why the total kinetic energy of the products of this decay is approximately 34 MeV . Assume the π^- is stationary.

(2)

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- (iii) State which two conservation laws could be used to calculate the kinetic energy of the μ^- and the $\bar{\nu}_\mu$ just after the decay of the π^- .

(2)

- *(iv) The muons are produced at a height of 10 km in the atmosphere. The velocity of the muons is $0.99c$. The average lifetime for muons is normally $2.2\mu\text{s}$ and yet muons produced in the upper atmosphere are found in significant numbers at sea level.

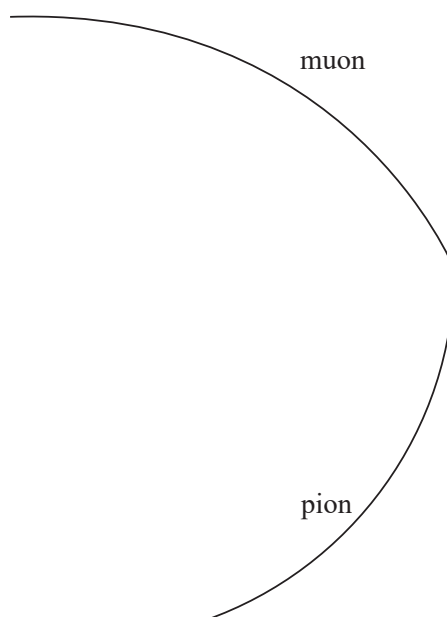
Discuss this apparent anomaly.

(6)

(Total for Question 16 = 16 marks)



- 18** A negatively charged pion decays into a muon and an antineutrino. The diagram shows tracks in a particle detector formed in such an event.



- (a) Deduce whether the antineutrino is charged, giving two reasons for your decision.

(2)

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- (b) Write a particle equation to represent this decay.

(1)

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- (c) According to the standard model, the pion and muon are classified within two different groups of particles.

State which group each particle belongs to and describe the two groups.

(4)

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- (d) The momentum of the pion just before it decays is $9.1 \times 10^{-20} \text{Ns}$.

Determine the magnetic flux density of the magnetic field which acts in the detector and state its direction.

Scale of diagram 1 cm represents 10 cm

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

(4)

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Magnetic flux density = ...

Direction of magnetic field = ...



(e) Use a vector diagram to determine the momentum of the antineutrino.

The initial momentum of the muon is $1.59 \times 10^{-19} \text{ N s}$.

(5)

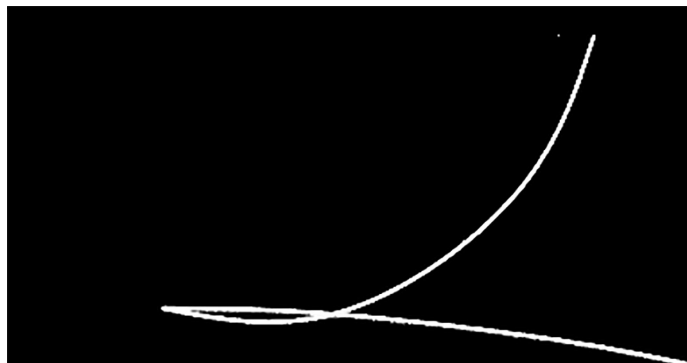
Momentum of antineutrino = ...

Direction of antineutrino = ...

(Total for Question 18 = 16 marks)



- 16 The bubble chamber photograph shows tracks made by a proton and a pion. The proton and pion were both created by the decay of a lambda particle. No other particles were produced.



- *(a) Explain how observations and measurements from the photograph can be used to establish information about the lambda particle.

(6)

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- (b) The lambda particle consists of up, down and strange quarks.

Explain how the conservation of charge, baryon number and lepton number apply to the decay of the lambda particle.

(3)

- (c) Write an equation to represent the decay of the lambda (Λ) particle.

(1)

- (d) The rest mass of the lambda particle is $1115 \text{ MeV}/c^2$.

- (i) Calculate this mass in kg.

(3)

Mass = ... kg



(ii) The rest mass of a proton is $940 \text{ MeV}/c^2$. The rest mass of a pion is $140 \text{ MeV}/c^2$.

The kinetic energy of the lambda particle just before decay is 4.95 GeV .

Calculate the total kinetic energy of the proton and pion in MeV .

(3)

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Total kinetic energy = ... MeV

(Total for Question 16 = 16 marks)



15 The discovery of the Higgs particle was an important contribution to our understanding of particle physics.

- (a) Describe the standard model for subatomic particles. You should identify the fundamental particles and the composition of the particles we can observe.

(5)

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- (b) The mass of the Higgs particle is 2.2×10^{-25} kg.

Calculate this mass in GeV/c^2 .

(3)

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Mass = ... GeV/c^2



- (c) The Higgs particle was discovered using the Large Hadron Collider (LHC) in 2012. Two beams of very high energy protons, moving in opposite directions, were made to collide.

(i) Explain the need for such high energy collisions.

(3)

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- (ii) The beams of protons are contained within a ring of superconducting magnets.

Calculate the momentum of a proton in a beam.

(3)

magnetic field strength = 8.3 T

circumference of the ring = 27 km

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Momentum = ...

- (iii) State the total momentum of the products of the collision between the two beams of protons.

(1)

Total momentum = ...



(d) The LHC accelerates protons until they gain energies of about 7 TeV.

A student used the equation $E_k = \frac{p^2}{2m}$ to predict the energy of a proton in the beam, using the momentum calculated in (c)(ii), but found the energy was far higher than 7 TeV.

Explain why.

(2)

(Total for Question 15 = 17 marks)



MARK SCHEMES

official mark schemes



8	C	Most alpha particles go straight through.	The atom is mainly empty space.	1
	A the observation is incorrect B the observation is incorrect D the observation is correct but this is not the corresponding conclusion			



Question Number	Acceptable answers	Additional guidance	Mark
10	C		1

(Total for Multiple Choice Questions = 10 marks)



9	The only correct answer is A <i>B is not correct because the charge on an Au nucleus is $79 \times 1.6 \times 10^{-19} C$</i> <i>C is not correct because the charge on an alpha particle is $2 \times 1.6 \times 10^{-19} C$</i> <i>D is not correct because the charges have not been converted to C</i>		1
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10	The only correct answer is B <i>A is not correct because it is a correct conclusion</i> <i>C is not correct because it is a correct conclusion</i> <i>D is not correct because it is a correct conclusion</i>		1
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(Total for Multiple Choice Questions = 10 marks)



Question Number	Acceptable answers	Additional guidance	Mark
1	The only correct answer is C A is not the correct answer, as there are 8 protons and 9 neutrons. B is not the correct answer, as there are 8 protons and 9 neutrons. D is not the correct answer, , as there are 8 protons and 9 neutrons.		1



8	The only correct answer is C A is not the correct answer, as P.E. increases and speed decreases as particle approaches nucleus B is not the correct answer, as P.E. increases and speed decreases as particle approaches nucleus D is not the correct answer, as P.E. increases and speed decreases as particle approaches nucleus		1
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9	The only correct answer is D A is not the correct answer, as electrons will not deflect particle. B is not the correct answer, as neutral atom will not deflect particle. C is not the correct answer, as this cannot be concluded from observing just one particle.		1
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Question Number	Acceptable Answer	Additional Guidance	Mark
1	The only correct answer is A (structure of an atom) B is not the correct answer, as this experiment investigated the structure of the atom C is not the correct answer, as this experiment investigated the structure of the atom D is not the correct answer, as this experiment investigated the structure of the atom		1



Question Number	Acceptable Answer	Additional Guidance	Mark																																																				
*4	This question assesses a student’s ability to show a coherent and logical structured answer with linkage and fully-sustained reasoning. Indicative content: IC1 Most of the particles are not deflected as they pass through the gold foil IC2 This indicates that there is mostly empty space inside the gold atom IC3 Some particles were deflected from their path by small angles IC4 This indicates a charged centre (was deflecting alpha particles) IC5 A very small proportion of particles were deflected through more than 90° IC6 This indicates that most of the mass of the atom is concentrated in the nucleus	Marks are awarded for indicative content and for how the answer is structured and shows lines of reasoning. The following table shows how the marks should be awarded for indicative content. <table><tr><th>Number of indicative marking points seen in answer</th><th>Number of marks awarded for indicative marking points</th></tr><tr><td>6</td><td>4</td></tr><tr><td>5–4</td><td>3</td></tr><tr><td>3–2</td><td>2</td></tr><tr><td>1</td><td>1</td></tr><tr><td>0</td><td>0</td></tr></table> <table><tr><th></th><th>Number of marks awarded for structure of answer and sustained line of reasoning</th></tr><tr><td>Answer shows a coherent and logical structure with linkages and fully sustained lines of reasoning demonstrated throughout</td><td>2</td></tr><tr><td>Answer is partially structured with some linkages and lines of reasoning</td><td>1</td></tr><tr><td>Answer has no linkages between points and is unstructured</td><td>0</td></tr></table> Total marks awarded is the sum of marks for indicative content and the marks for structure and lines of reasoning <table><tr><th>IC points</th><th>IC mark</th><th>Max linkage mark</th><th>Max final mark</th></tr><tr><td>6</td><td>4</td><td>2</td><td>6</td></tr><tr><td>5</td><td>3</td><td>2</td><td>5</td></tr><tr><td>4</td><td>3</td><td>1</td><td>4</td></tr><tr><td>3</td><td>2</td><td>1</td><td>3</td></tr><tr><td>2</td><td>2</td><td>0</td><td>2</td></tr><tr><td>1</td><td>1</td><td>0</td><td>1</td></tr><tr><td>0</td><td>0</td><td>0</td><td>0</td></tr></table>	Number of indicative marking points seen in answer	Number of marks awarded for indicative marking points	6	4	5–4	3	3–2	2	1	1	0	0		Number of marks awarded for structure of answer and sustained line of reasoning	Answer shows a coherent and logical structure with linkages and fully sustained lines of reasoning demonstrated throughout	2	Answer is partially structured with some linkages and lines of reasoning	1	Answer has no linkages between points and is unstructured	0	IC points	IC mark	Max linkage mark	Max final mark	6	4	2	6	5	3	2	5	4	3	1	4	3	2	1	3	2	2	0	2	1	1	0	1	0	0	0	0	6
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2	2	0	2																																																				
1	1	0	1																																																				
0	0	0	0																																																				

(Total for Question 4 = 6 marks)



Question Number	Acceptable answers		Additional guidance	Mark
14 (a)	- The curved surface is (analogous to) a radial field (as $h \propto 1/r$ then) potential (energy) $\propto 1/r$ - compares with $V \propto 1/r$ around a point charge	(1) (1) (1)		3
14 (b)	Maximum of 4 marks for MP1,3,5 and any one of MP2,4 or 6 - a few alpha's reflect straight back - can be represented by the ball bearing being directly aimed at the centre of the "hill" - some alpha's slightly deflected/through small angles - can be represented by the ball bearing being aimed close to the centre line of the hill - Many/most alpha's undeflected - can be shown by aiming the ball bearing so that it touches/misses the edge of the hill	(1) (1) (1) (1) (1) (1)	accept deflect through large angles/more than 90° MP2 dependent on being linked to MP1 MP4 dependent on being linked to MP3 MP6 dependent on being linked to MP5	4 Max

(Total for Question 14 = 7 marks)



Question Number	Acceptable answers	Additional guidance	Mark
15(a)	Before scattering experiment: - atom containing equally distributed mass/charge (1) After experiment: - very small nucleus containing (almost all) the mass of the atom (1) - atom mainly empty space (1) - nucleus is charged (1)	alt: reference to 'plum pudding model'	4
15(b)	- Use of $VV = QQ/4\pi\epsilon\epsilon_0rr$ (1) - Conversion MeV to J (1) - Use of $VV = WW/QQ$ (1) $r = 3.0 \times 10^{-14} \text{ m}$ (1)	allow for $Q = 2$ or 79, accept $VV = kkQQ/rr$ Must use $e = 1.6 \times 10^{-19} \text{ C}$ to convert atomic number to C <u>Example of calculation:</u> $7.7 \times 10^6 \text{ eV} \times 1.6 \times 10^{-19} \text{ J eV}^{-1}$ $= 8.99 \times 10^9 \text{ N m}^2 \text{ C}^{-2} \times 2 \times 79 \times (1.6 \times 10^{-19} \text{ C})^2 \div rr$ $rr = 2.27 \times 10^{-7} \div 7.7 \times 10^6$ $= 2.95 \times 10^{-14} \text{ m}$	4

15(c)	An explanation that makes reference to the following points: Observation 1 • (the fraction of alpha scattering is less for aluminium) so the force of repulsion is less (at a given distance) (1) • therefore the charge on an aluminium nucleus is less than on gold nucleus (1) Observation 2		4
	• (the E_k is less for scattered alpha for aluminium) so • recoiling nucleus must have some/more kinetic energy (1) The mass of an aluminium nucleus is less than mass of a gold nucleus (1)		

(Total for Question 15 = 12 marks)

Question Number	Acceptable answers	Additional guidance	Mark
17(a)	- The atom is mainly empty space (1) - All/most of mass of the atom is in a nucleus/centre which is charged (1) - The nucleus is small compared to the atom (1)	Accept dense and charged	3
17(b)(i)	- Use of $V = Q/4\pi\epsilon_0 r$ (1) - Identifies number of (positive) charges for alpha or gold nucleus (1) - Use of $W = VQ$ (1) $r = 5 \times 10^{-14}$ m so textbook statement is correct Or $V = 7.27 \times 10^{-13}$ J so textbook statement is correct (MP4 dependent on MP1) (1)	<u>Example of calculation</u> 7.30×10^{-13} J = $\left(\frac{8.99 \times 10^9 \text{ Nm}^2 \text{ C}^{-2} \times 79 \times 1.6 \times 10^{-19} \text{ C}}{r} \right) \times 2 \times 1.6 \times 10^{-19} \text{ C}$ $r = 4.98 \times 10^{-14}$ m	4
17(b)(ii)	- Use of $E_k = \frac{p^2}{2m}$ (1) - Converts atomic mass to kg (1) $p = 9.9 \times 10^{-20}$ kg m s⁻¹ (1)	Accept Use of $E_k = \frac{1}{2}mv^2$ and $p = mv$ <u>Example of calculation</u> 7.30×10^{-13} J = $p^2/2 \times 4 \times 1.66 \times 10^{-27}$ kg $p = 9.9 \times 10^{-20}$ kg m s ⁻¹	3
17(c)(i)	(Total) kinetic energy conserved (1)		1
17(c)(ii)	- The gold atom/nuclei recoil (1) Or the gold atoms/nuclei gain kinetic energy Or the gold atoms/nuclei are displaced/move	Accept Small/negligible increase in thermal energy (in the gold foil)	1

(Total for Question 17 = 12 marks)



***12(a)**

This question assesses a student's ability to show a coherent and logically structured answer with linkages and fully sustained reasoning.

Marks are awarded for indicative content and for how the answer is structured and shows lines of reasoning.

The table shows how the marks should be awarded for indicative content and structure and lines of reasoning.

Number of indicative marking points seen in answer	Number of marks awarded for indicative marking points
6	4
5-4	3
3-2	2
1	1
0	0

	Number of marks awarded for structure of answer and sustained line of reasoning
Answer shows a coherent and logical structure with linkages and fully sustained lines of reasoning demonstrated throughout	2
Answer is partially structured with some linkages and lines of reasoning	1
Answer has no linkages between points and is unstructured	0

Indicative content:

1. As the temperature of the gas increases the (average) speed/ E_k of the atoms increases
2. Greater speed/ E_k so the momentum of the atoms increases
3. The rate/frequency of collision of atoms with the container walls increases **Or** the time between collisions with the walls decreases
4. The rate of change of momentum at the walls increases
5. Rate of change of momentum is equal to the force
6. Pressure is $\frac{\text{force}}{\text{area}}$ and the force (on the walls) is greater

IC Points	IC Mark	Max linkage mark avail.	Max final mark
6	4	2	6
5	3	2	5
4	3	1	4
3	2	1	3
2	2	0	2
1	1	0	1
0	0	0	0

IC3 and IC4 must include a mention of the walls/container

6

12(b)(i)	• Conversion of MeV to J (1) • See $Q_1 = 79 \times 1.6 \times 10^{-19}$ and $Q_2 = 2 \times 1.6 \times 10^{-19}$ (1) • Use of $V = \frac{Q}{4\pi\epsilon_0 r}$ and $W = QV$ (1) • $r = 4.1 \times 10^{-14}$ m (1)	<u>Example of calculation</u> $E_\alpha = 5.5 \times 10^6 \text{ eV} \times 1.6 \times 10^{-19} \text{ J eV}^{-1} = 8.8 \times 10^{-13} \text{ J}$ $8.8 \times 10^{-13} \text{ J} = \frac{79 \times 1.6 \times 10^{-19} \text{ C} \times 2 \times 1.6 \times 10^{-19} \text{ C}}{4\pi \times 8.85 \times 10^{-12} \text{ F m}^{-1} r}$ $r = \frac{3.64 \times 10^{-26} \text{ N m}^2}{8.8 \times 10^{-13} \text{ J}} = 4.1 \times 10^{-14} \text{ m}$	4
12(b)(ii)	• Electrons are behaving like waves (1) • wavelength = $\frac{h}{\text{momentum}}$ (1) • Electron wavelength must be similar to the atomic spacing in the foil (1)	MP3: Accept electron wavelength must be similar to the distance between (adjacent) nuclei	3
12(c)	• Electrons are excited to higher energy states / levels (by incident electrons) (1) • An electron returns to the lower energy state / level resulting in the emission of a <u>photon</u> (1) • The energy of the photon is equal to the difference of the energy states / levels (1) • Large difference in energy states / levels so as $E = hf$, radiation is high frequency (1)	For MP1 and MP2 allow • Electrons knock electrons out of low energy levels • Electrons cascade down to fill up the levels	4

(Total for Question 12 = 17 marks)



9	The only correct answer is B <i>A is not correct because a cyclotron uses a magnetic field</i> <i>C is not correct because a LINAC uses an electric field</i> <i>D is not correct because a LINAC does not use a magnetic field</i>	Cyclotron accelerated	1
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Question Number	Acceptable answers	Additional guidance	Mark
4	The only correct answer is D <i>A is not correct because the process described is the thermionic effect</i> <i>B is not correct because the process described is the thermionic effect</i> <i>C is not correct because the process described is the thermionic effect</i>		1



Question Number	Acceptable answers	Additional guidance	Mark
2	The only correct answer is B A is not the correct answer, as it is charged so could be accelerated. C is not the correct answer, as it is charged so could be accelerated. D is not the correct answer, as it is charged so could be accelerated.		1



5	The only correct answer is B (into the page) A is not the correct answer, as the positron is anticlockwise, the force is to the centre of the spiral and use of Flemings left hand rule C is not the correct answer, as the positron is anticlockwise, the force is to the centre of the spiral and use of Flemings left hand rule D is not the correct answer, as the positron is anticlockwise, the force is to the centre of the spiral and use of Flemings left hand rule		1
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Question Number	Acceptable answers	Additional guidance	Mark																												
*13(a)	This question assesses a student’s ability to show a coherent and logical structured answer with linkage and fully-sustained reasoning. Marks are awarded for indicative content and for how the answer is structured and shows lines of reasoning. The following table shows how the marks should be awarded for indicative content. <table><tr><th>Number of indicative points seen in answer</th><th>Number of marks awarded for indicative points</th></tr><tr><td>6</td><td>4</td></tr><tr><td>5-4</td><td>3</td></tr><tr><td>3-2</td><td>2</td></tr><tr><td>1</td><td>1</td></tr><tr><td>0</td><td>0</td></tr></table> Indicative content - There is an alternating p.d./E-field - P.d./E-field accelerates protons between dees - Magnetic field perpendicular to plane of dees - Proton path curved by magnetic field - As velocity of protons increases radius of path in dees increases - The time for which a proton is in a dee remains constant Or the frequency of p.d./E-field is constant	Number of indicative points seen in answer	Number of marks awarded for indicative points	6	4	5-4	3	3-2	2	1	1	0	0	Guidance on how the mark scheme should be applied: The mark for The following table shows how the marks should be awarded for structure and lines of reasoning <table><tr><td></td><td>Number of marks awarded for structure and lines of reasoning</td></tr><tr><td>Answer shows a coherent and logical structure with linkage and fully sustained lines of reasoning demonstrated throughout</td><td>2</td></tr><tr><td>Answer is partially structured with some linkages and lines of reasoning</td><td>1</td></tr><tr><td>Answer has no linkage between points and is unstructured</td><td>0</td></tr></table> <table><tr><th>Number of IC points</th><th>Possible linkage marks</th></tr><tr><td>0, 1</td><td>0</td></tr><tr><td>2, 3</td><td>1</td></tr><tr><td>4, 5, 6</td><td>2</td></tr></table> IC2 accept ‘in the gap’ for between dees. Accept increases E_k for accelerates IC3 accept vertical or upwards for perpendicular to plane. IC5 accept reference to $r = p/BQ$		Number of marks awarded for structure and lines of reasoning	Answer shows a coherent and logical structure with linkage and fully sustained lines of reasoning demonstrated throughout	2	Answer is partially structured with some linkages and lines of reasoning	1	Answer has no linkage between points and is unstructured	0	Number of IC points	Possible linkage marks	0, 1	0	2, 3	1	4, 5, 6	2	6
Number of indicative points seen in answer	Number of marks awarded for indicative points																														
6	4																														
5-4	3																														
3-2	2																														
1	1																														
0	0																														
	Number of marks awarded for structure and lines of reasoning																														
Answer shows a coherent and logical structure with linkage and fully sustained lines of reasoning demonstrated throughout	2																														
Answer is partially structured with some linkages and lines of reasoning	1																														
Answer has no linkage between points and is unstructured	0																														
Number of IC points	Possible linkage marks																														
0, 1	0																														
2, 3	1																														
4, 5, 6	2																														



13(b)	For the proton beam - Proton beam deposits more energy in tumour than the X-rays (1) - Proton beam results in less energy absorbed by surrounding tissue compared to X-rays (1)	Accept converse statement for both marks related to X-rays	2
13(c)	Any two from: - Cost of treatment reduced in the long-term (1) - Better chances of success compared with previous treatment (1) - Fewer side effects compared to previous Or patient recover more quickly (1)		2

(Total for Question 13 = 10 marks)



Question Number	Acceptable Answer	Additional Guidance	Mark
7(a)	An explanation that makes reference to the following points: - The potential difference creates an electric field - An (electric) field/force does work on the electrons (increasing their kinetic energy) Or an (electric) field/force accelerates the electrons (increasing their velocity)		2
7(b)(i)	(Perpendicularly) out of the page - The force is perpendicular to the magnetic field and the direction of (conventional) current Or an application of Fleming's Left-Hand Rule	Accept movement of electrons for current	2
7(b)(ii)	An explanation that makes reference to the following points: - There would be a force (of constant magnitude) on the electron perpendicular to its direction of motion - Causing an acceleration towards the centre of a circle	Accept reference to centripetal force for MP1	2
7(c)(i)	- Use of $F = BQv$ and $F = EQ$ - Algebra to show $v = \frac{E}{B}$		2
7(c)(ii)	- Use of $W = QV$ and $E_k = \frac{1}{2}mv^2$ - Use of $v = \frac{E}{B}$ $\frac{e}{m} = 1.7 \times 10^{11} \text{ C kg}^{-1}$	<u>Example of calculation:</u> $v = \frac{E}{B} = \frac{1.4 \times 10^4 \text{ V m}^{-1}}{1.5 \times 10^{-3} \text{ T}} \quad \frac{e}{m} = \frac{v^2}{2V}$ $\frac{e}{m} = \frac{(9.33 \times 10^6 \text{ m s}^{-1})^2}{2 \times 250 \text{ V}} = 1.74 \times 10^{11} \text{ C kg}^{-1}$	3
7(d)	- The hydrogen ion must be (about 2000 times) more massive than the electron Or the electron must be (about 2000 times) less massive than the hydrogen ion	Accept "proton" for "hydrogen ion"	1

(Total for Question 7 = 12 marks)



Question Number	Acceptable Answer	Additional Guidance	Mark
18(a)	- The frequency of the ac supply is constant (1) - The time in a tube = length of tube /speed (1) - As (the beam/particles/ions) speed increases (1) - The time between beam exiting each consecutive tube is constant (1)	Accept time in each tube is constant	4
18(b)(i)	- Determines charge on the ion: $80e$ (1) - Use of $W = VQ$ (1) - Recognises Nucleon Number: 238 (1) $V = 600$ MV (1)	<u>Example of calculation</u> Ion charge = $80e$ Kinetic energy of U ion = $200 \text{ MeV} \times 238$ U ion accelerated to a kinetic energy $80e \times V = 200 \text{ MeV} \times 238$ $V = 595 \text{ MV}$	4
18(b)(ii)	- Conversion MeV to J (1) - Use of $E_k = \frac{1}{2}mv^2$ (1) $v/c = 65.3\%$ (1)	<u>Example of calculation</u> E_k of U ion in J = $200 \times 10^6 \text{ eV} \times 238 \times 1.6 \times 10^{-19} \text{ C}$ $= 7.616 \times 10^{-9} \text{ J}$ $\frac{1}{2} 238 \times 1.66 \times 10^{-27} \text{ kg} \times v^2 = 7.616 \times 10^{-9} \text{ J}$ $v = 1.96 \times 10^8 \text{ m s}^{-1}$ $v/c = 1.96 \times 10^8 \text{ m s}^{-1} / 3.0 \times 10^8 \text{ m s}^{-1} = 65.3\%$ Allow use of 1.67×10^{-27} to calculate final value Note that 238 can be omitted on both sides of this equation: Kinetic energy of U ion in J = $200 \text{ MeV} \times 1.6 \times 10^{-19} \text{ C}$ $= 3.2 \times 10^{-11} \text{ J}$ $\frac{1}{2} 1.66 \times 10^{-27} \text{ kg} \times v^2 = 3.2 \times 10^{-11} \text{ J}$ $v = 1.96 \times 10^8 \text{ m s}^{-1}$	3



18(c)	2 max - This isotope of magnesium has a lot more neutrons than the usual isotope (1) - Uranium has (far) more neutrons than protons (1) - so is likely to produce neutron rich isotopes (1)	Accept products produced with a lot of neutrons	2
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(Total for Question 18 = 13 marks)



Question Number	Acceptable answers	Additional guidance	Mark																																
*15 (a)	This question assesses a student's ability to show a coherent and logically structured answer with linkages and fully-sustained reasoning. Marks are awarded for indicative content and for how the answer is structured and shows lines of reasoning. The following table shows how the marks should be awarded for indicative content. Indicative content: IC1: set of (metal drift) tubes (in a line) IC2: electrons accelerated by electric field/potential difference IC3: acceleration takes place in the gaps between tubes IC4: adjacent tubes connected to opposite terminals of a power supply or opposite charge/polarity IC5: power supply/p.d./electric field is alternating (so that as electron emerges from one tube the next tube is positive) IC6: time spent in each tube must be the same so as the electrons travel faster the tubes must be longer / gaps between get longer	<table border="1"> <thead> <tr> <th>IC points</th><th>IC mark</th><th>Max linkage mark available</th><th>Max final mark</th></tr> </thead> <tbody> <tr> <td>6</td><td>4</td><td>2</td><td>6</td></tr> <tr> <td>5</td><td>3</td><td>2</td><td>5</td></tr> <tr> <td>4</td><td>3</td><td>1</td><td>4</td></tr> <tr> <td>3</td><td>2</td><td>1</td><td>3</td></tr> <tr> <td>2</td><td>2</td><td>0</td><td>2</td></tr> <tr> <td>1</td><td>1</td><td>0</td><td>1</td></tr> <tr> <td>0</td><td>0</td><td>0</td><td>0</td></tr> </tbody> </table> IC points 1 and 4 may be awarded with well-drawn diagram IC6 accept reference to distance between centres/ends of tubes must increase to give a fixed alternating frequency	IC points	IC mark	Max linkage mark available	Max final mark	6	4	2	6	5	3	2	5	4	3	1	4	3	2	1	3	2	2	0	2	1	1	0	1	0	0	0	0	6
IC points	IC mark	Max linkage mark available	Max final mark																																
6	4	2	6																																
5	3	2	5																																
4	3	1	4																																
3	2	1	3																																
2	2	0	2																																
1	1	0	1																																
0	0	0	0																																
15 (b)	- High energy electrons will have a short (de Broglie) wavelength (1) - The wavelength needs to be comparable/smaller than proton size (1)		2																																



15 (c)(i)	- units eV (energy) base units: $\text{kg m}^2 \text{s}^{-2}$ Or base units of momentum: kg m s^{-1} (1) - divide energy by units of speed (c) m s^{-1} gives kg m s^{-1} which are units of momentum Or multiply units of momentum by speed (c) m s^{-1} to give units of energy $\text{kg m}^2 \text{s}^{-2}$ (1)		2
15(c)(ii)	- resolves a y-component or x-component of electron momentum (1) - applies momentum conservation in x-direction or y-direction (1) - comparison of total momentum after Or momentum of proton after plus comment (1) Alternative: - draws a vector triangle - Uses cosine rule - Calculates angle from three sides = 20.4°	<u>Example of calculation</u> $p_y = 9.1 (\text{GeV}/c) \sin 20 = 3.1 \text{ GeV}/c$ $p_x = 9.1 (\text{GeV}/c) \cos 20 = 8.55 \text{ GeV}/c$ $p_x \text{ of proton} = 20 (\text{GeV}/c) - 8.55 (\text{GeV}/c) = 11.45 \text{ GeV}/c$ $p_{\text{proton}} = \sqrt{3.1^2 + 11.45^2} = 11.86 \text{ GeV}/c$ Alternative: $p_y = 9.1 (\text{GeV}/c) \sin 20 = 3.1 \text{ GeV}/c = 11.9 (\text{GeV}/c) \sin \theta$ $\theta = 15.2$ So total p after = $11.9 \text{ GeV}/c \cos 15.2 + 9.1 (\text{GeV}/c) \cos 20$ $= 11.5 + 8.55 = 20.05 \text{ GeV}/c$	3
15(c)(iii)	(total) kinetic energy not conserved (1)		1

(Total for Question 14 = 14 marks)



Question Number	Acceptable Answer	Additional Guidance	Mark
11(a)(i)	An explanation that makes reference to the following points: - The velocity/momentum increases as the energy of the protons increases (1) $r = \frac{p}{Bq}$ and $p=mv$ so the magnetic flux density must increase (to keep r constant). - Or $r = \frac{p}{Bq}$ and $E_k = \frac{p^2}{2m}$ so the magnetic flux density must increase (to keep r constant). - Or $F = \frac{mv^2}{r}$ and $F = Bqv$ so the magnetic flux density must increase (to keep r constant) (1)		2



11(a)(ii)	- Radius calculated - Use of $F = \frac{mv^2}{r}$ - Use of $F = Bqv$ $B = 7.3 \times 10^{-5} \text{ T}$	(1) (1) Allow use of $p = mv$ for MP2 (1) and use of $r = \frac{p}{Bq}$ for MP3 (1) <u>Example of calculation</u> $r = \frac{\text{circumference}}{2\pi} = \frac{27 \times 10^3 \text{ m}}{2\pi} = 4.30 \times 10^3 \text{ m}$ $F = \frac{1.67 \times 10^{-27} \text{ kg} \times (3.0 \times 10^7 \text{ m s}^{-1})^2}{4.30 \times 10^3 \text{ m}} = 3.50 \times 10^{-16} \text{ N}$ $B = \frac{3.50 \times 10^{-16} \text{ N}}{1.6 \times 10^{-19} \text{ C} \times 3.0 \times 10^7 \text{ m s}^{-1}} = 7.28 \times 10^{-5} \text{ T}$	4
11(a)(iii)	- Conversion to joule - Use of $\Delta E = c^2 \Delta m$ $m = 2.4 \times 10^{-23} \text{ (kg)}$	(1) <u>Example of calculation</u> (1) $E = 13\,600 \times 10^9 \text{ eV} \times 1.6 \times 10^{-19} \text{ J eV}^{-1} = 2.18 \times 10^{-6} \text{ J}$ (1) $m = \frac{2.18 \times 10^{-6} \text{ J}}{(3.0 \times 10^8 \text{ m s}^{-1})^2} = 2.42 \times 10^{-23} \text{ kg}$	3



*11(b)	This question assesses a student’s ability to show a coherent and logical structured answer with linkage and fully-sustained reasoning Indicative content: IC1 In a fixed target collision there is momentum before the collision so there is momentum after the collision IC2 So particle(s) created must have some kinetic energy IC3 So not all kinetic energy converted to mass IC4 In a colliding beam experiment total initial momentum is zero (if the colliding particles have the same mass and speed) IC5 Momentum after the collision will be zero IC6 So (almost) all of the kinetic energy is converted to mass	Marks are awarded for indicative content and for how the answer is structured and shows lines of reasoning. The following table shows how the marks should be awarded for indicative content. <table><tr><th>Number of indicative marking points seen in answer</th><th>Number of marks awarded for indicative marking points</th></tr><tr><td>6</td><td>4</td></tr><tr><td>5–4</td><td>3</td></tr><tr><td>3–2</td><td>2</td></tr><tr><td>1</td><td>1</td></tr><tr><td>0</td><td>0</td></tr></table> <table><tr><th></th><th>Number of marks awarded for structure of answer and sustained line of reasoning</th></tr><tr><td>Answer shows a coherent and logical structure with linkages and fully sustained lines of reasoning demonstrated throughout</td><td>2</td></tr><tr><td>Answer is partially structured with some linkages and lines of reasoning</td><td>1</td></tr><tr><td>Answer has no linkages between points and is unstructured</td><td>0</td></tr></table> Total marks awarded is the sum of marks for indicative content and the marks for structure and lines of reasoning. <table><tr><th>IC points</th><th>IC mark</th><th>Max linkage mark</th><th>Max final mark</th></tr><tr><td>6</td><td>4</td><td>2</td><td>6</td></tr><tr><td>5</td><td>3</td><td>2</td><td>5</td></tr><tr><td>4</td><td>3</td><td>1</td><td>4</td></tr><tr><td>3</td><td>2</td><td>1</td><td>3</td></tr><tr><td>2</td><td>2</td><td>0</td><td>2</td></tr><tr><td>1</td><td>1</td><td>0</td><td>1</td></tr><tr><td>0</td><td>0</td><td>0</td><td>0</td></tr></table>	Number of indicative marking points seen in answer	Number of marks awarded for indicative marking points	6	4	5–4	3	3–2	2	1	1	0	0		Number of marks awarded for structure of answer and sustained line of reasoning	Answer shows a coherent and logical structure with linkages and fully sustained lines of reasoning demonstrated throughout	2	Answer is partially structured with some linkages and lines of reasoning	1	Answer has no linkages between points and is unstructured	0	IC points	IC mark	Max linkage mark	Max final mark	6	4	2	6	5	3	2	5	4	3	1	4	3	2	1	3	2	2	0	2	1	1	0	1	0	0	0	0
Number of indicative marking points seen in answer	Number of marks awarded for indicative marking points																																																					
6	4																																																					
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IC points	IC mark	Max linkage mark	Max final mark																																																			
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5	3	2	5																																																			
4	3	1	4																																																			
3	2	1	3																																																			
2	2	0	2																																																			
1	1	0	1																																																			
0	0	0	0																																																			

6

(Total for Question 11 = 15 marks)



Question Number	Acceptable Answer	Additional Guidance	Mark
13(a)	(isotopes are atoms/nuclides with the) same number of protons but different numbers of neutrons/nucleons (in the nucleus) (1)	Ignore references to the number of electrons in the atoms Do not credit mass number or atomic number	1
13(b)	- Use of $W = QV$ (1) - Use of $KE = \frac{1}{2}mv^2$ (1) - Use of $1u = 1.66 \times 10^{-27} \text{ kg}$ (1) $v = 2.16 \times 10^5 \text{ (m s}^{-1}\text{)}$ (1)	Example of calculation: $\frac{1}{2}mv^2 = eV$ $\therefore v = \sqrt{\frac{2 \times 1.6 \times 10^{-19} \text{ C} \times 8.5 \times 10^3 \text{ V}}{(34.97 \times 1.66 \times 10^{-27}) \text{ kg}}} = 2.16 \times 10^5 \text{ ms}^{-1}$	4
13(c)(i)	- Electric field vertically downwards (from top plate to bottom plate) (1) - Magnetic field into paper (1)		2
13(c)(ii)	- Use of $E = \frac{V}{d}$ (1) - Use of $F_E = EQ$ (1) - Use of $F_M = BQv$ (1) - Show that these forces are equal (if v is $2.2 \times 10^5 \text{ m s}^{-1}$) and hence state that B is suitable (1)	Do not award MP4 if incorrect ion charge used Example of calculation: $E = \frac{V}{d} = \frac{135 \text{ V}}{2.5 \times 10^{-2} \text{ m}} = 5400 \text{ V m}^{-1}$ $F = EQ = 5400 \text{ V m}^{-1} \times 1.6 \times 10^{-19} \text{ C} = 8.6 \times 10^{-16} \text{ N}$ $F = BQv = 24.5 \times 10^{-3} \text{ T} \times 1.6 \times 10^{-19} \text{ C} \times 2.2 \times 10^5 \text{ ms}^{-1} = 8.6 \times 10^{-16} \text{ N}$	4



13(d)(i)	- The ions experience a force perpendicular to their velocity (and the magnetic field) (1) - The (resultant) force on the ions causes an acceleration at right angles to their velocity (1) Or There is a magnetic force acting towards the centre of the path (1)	For velocity accept direction of motion or direction of travel	2
13(d)(ii)	- Use of $r = \frac{mv}{BQ}$ (1) $r = 0.23 \text{ m}$ (1)	<u>Example of calculation:</u> $r = \frac{mv}{BQ}$ $= \frac{(34.97 \times 1.66 \times 10^{-27}) \text{ kg} \times 2.2 \times 10^5 \text{ ms}^{-1}}{0.35 \text{ T} \times 1.6 \times 10^{-19} \text{ C}} = 0.228 \text{ m}$	2
13(d)(iii)1	path drawn with less curvature (less overall deflection) (1)	MP1 awarded for path in the magnetic field	1
13(d)(iii)2	- ions are more massive (1) - ions have the same charge so the radius of the path would be greater (1)		2

(Total for Question 13 = 18 marks)



10	The only correct answer is C <i>A is not correct because lepton number is not conserved</i> <i>B is not correct because charge conservation is not obeyed</i> <i>D is not correct because charge conservation is not obeyed</i>	$p \rightarrow n + \beta^+ + \nu$	1
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(Total for Multiple Choice Questions = 10 marks)



Question Number	Acceptable answers	Additional guidance	Mark
1	B		1



Question Number	Acceptable answers	Additional guidance	Mark		
2	The only correct answer is C <table><tr><td>1</td><td>0</td></tr></table>	1	0	A and B are incorrect as a neutron has mass D is incorrect as a neutron is neutral	1
1	0				



Question Number	Acceptable answers	Additional guidance	Mark
5	The only correct answer is B $n + \pi^+$	A, C and D do not follow conservation laws	1



8	The only correct answer is C $\frac{1.67 \times 10^{-27} \times (3.00 \times 10^8)^2}{1.60 \times 10^{-10}}$	A,B and D all contain numerical errors	1
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Question Number	Acceptable answers	Additional guidance	Mark
2	The only correct answer is C A is not correct as the particle is a meson B is not correct as the particle is a meson D is not correct as the mass cannot be negative		1



Question Number	Acceptable answers	Additional guidance	Mark
1	The only correct answer is A <i>B is not correct because an electron has a much smaller mass</i> <i>C is not correct because a neutron has no charge</i> <i>D is not correct because a positron has a much smaller mass and is positive</i>		1



Question Number	Acceptable answers	Additional guidance	Mark
2	The only correct answer is C A is not the correct answer, as a baryon has three quarks. B is not the correct answer, as leptons are fundamental particles D is not the correct answer, as a nucleon is a proton or neutron		1



Question Number	Acceptable answers	Additional guidance	Mark
4	The only correct answer is A B is not the correct answer, as both mass and lifetime both increase. C is not the correct answer, as both mass and lifetime both increase. D is not the correct answer, as both mass and lifetime both increase.		1



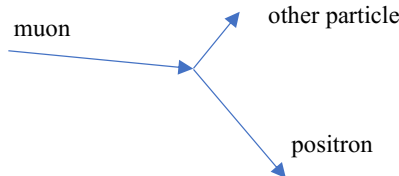
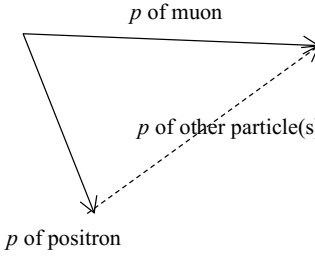
Question Number	Acceptable answers	Additional guidance	Mark
13(a)	- Identifies mass of antiproton is the same as proton (1) - Convert kg to J (1) - Convert J to eV (1) - Mass = 940 (MeV/c²) (1)	MP1: use of 1.67×10^{-27} kg <u>Example of calculation</u> $m = \frac{1.67 \times 10^{-27} \text{ kg} \times (3.0 \times 10^8)^2 (\text{m s}^{-1})^2}{1.6 \times 10^{-13} \text{ J MeV}^{-1}}$ $m = 939 \text{ MeV/c}^2$	4
13(b)	Maximum 4 out of 5 - Applies conservation of charge number (1) - Applies conservation of baryon number (1) - The momentum is conserved if the products have zero (total) momentum (1) - Energy required to create the extra mass of the two particles Or calculates $\Delta m = 1880 \text{ MeV/c}^2$ (1) - So possible if the protons can be given the energy by accelerating each beam through (at least) 940 MeV Or This can come from (a loss of) kinetic energy of protons (1)	eg +1 +1 = +1 +1 +1 -1 eg +1 +1 = +1 +1 +1 -1 “show that” value gives 1800 MeV/c^2 Accept Each beam needs an energy of (at least) 940 MeV Or 900 MeV if using “show that” value	4

(Total for Question 13 = 8 marks)



Question Number	Acceptable answers	Additional guidance	Mark
14(a)	Any two from: - Each lepton has an antiparticle (1) - Baryon number = 0 (1) - Leptons are fundamental particles (1) - Leptons interact via the weak force (1) - Leptons have a lepton number which isn't zero (1)		2
14(b)	- Correct symbols for positive muon and positron (1) - Correct symbols for neutrino and antineutrino (1)	$\mu^+ e^+$ $(\mu^+ \rightarrow e^+) + \nu_e + \bar{\nu}_\mu$	2
14(c)	- Magnetic field is used to curve the track Or Magnetic field exerts a centripetal force (1) - The direction of curvature indicates whether the charge is positive or negative (1) - It enables the momentum of particles to be determined (1)		3



14(d)	- The path of the positron has a different direction to that of the muon Or radius of curvature of each path is different - Momentum of positron is different to that of muon - Momentum is conserved - So a further particle(s) must be produced MP4 depends on MP3	MP1 and 4 accept a sketch showing other particle direction eg  The labelled sketch below would gain 4 marks 	4
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(Total for Question 14 = 11 marks)

Question Number	Acceptable Answer	Additional Guidance	Mark
15(a)	- Correct symbol for pion and neutron (1) - Pion marked positive (1)	Do not award MP1 if an additional symbol appears <u>Example</u> $(\Sigma^+) \rightarrow \pi^+ + n$ Ignore 0 if written next to n	2
15(b)	- Charge: $+1 \rightarrow +1 + 0$ (1) - Baryon number: $1 \rightarrow 0 + 1$ (1)		2
15(c)	- Three quarks (1) (s) u u (1)		2
15(d)(i)	The neutron is a neutral particle Or the neutron is not charged Or neutrons do not produce ionisation (1)		1
15(d)(ii)	- Measures radius 3.5 cm [range 3.0 cm to 9.0 cm] (1) - Uses scale correctly ($\times 15$) (1) - Use of $r = p/BQ$ with $Q = 1.6 \times 10^{-19} \text{ C}$ (1) $B = 1.3 \text{ T}$ [value consistent with their measured scaled radius note 3.0 cm leads to 1.5 T and 9.0 cm leads to 0.51 T] (1)	<u>Example of calculation</u> $r = 0.035 \times 15 = 0.525 \text{ m}$ Typical range after scaling 0.45 to 1.35 m $0.525 \text{ m} = \frac{1.1 \times 10^{-19} \text{ N s}}{B \times 1.6 \times 10^{-19} \text{ C}}$ $B = 1.3 \text{ T}$	4

(Total for Question 15 = 11 marks)



Question Number	Acceptable answers	Additional guidance	Mark
17 (a)	- Correct equation ignoring charges (1) - Charge on pion + (1)	$p + p \rightarrow p + n + \pi^+$	2
17 (b)	- p : u u d (1) - n : u d d (1) π^- : u $\bar{d}$ (1)	Accept labelled π^- : $\bar{u}$ d	3
17(c)	- Convert eV to J (1) - Convert J to kg (1) - mass = 2.5×10^{-28} (kg) (1)	<u>Example of calculation:</u> $m = \frac{140 \text{ (MeV/c}^2) \times 1.6 \times 10^{-13} \text{ J MeV}^{-1}}{(3 \times 10^8)^2 \text{ (m s}^{-1})^2}$ $m = 2.49 \times 10^{-28} \text{ (kg)}$	3
17(d)	- extra mass after collision is the mass of pion Or energy must be conserved so E_k is required for pion (1) - According to $\Delta E = c^2 \Delta m$ (if extra mass is pion) then ΔE required is 140 MeV Or extra mass is 140 MeV/c^2 so E required is 140 MeV (1) - Momentum conservation means that the (three) resulting particles after the collision must have some momentum/E_k (1) - The incoming proton needs 140 MeV plus the E_k of the product particles so statement is inaccurate (1)		4

(Total for Question 17 = 12 marks)

Question Number	Acceptable answers	Additional guidance	Mark
15(a)(i)	- Leaves no track (1) - Or the tracks present are opposite curvatures		1
15(a)(ii)	- proton is positive (1) - conservation of charge means pion is negative (1) - Or opposite curvature to proton means pion is negative	both marks can be given for 0 = +1 -1 with pion identified as negative.	2
15(a)(iii)	$(\Delta^0) \quad p^{(+)} + \pi^-$ (1)	Allow ecf if pion was stated as positive in (ii)	1
15(a)(iv)	- baryon number conserved - Or baryon number is +1 on both sides of equation - Or proton is baryon and the pion is not a baryon (1)		1
15(a)(v)	An explanation that makes reference to the following points: - The radius of the proton path is (very) large (compared with the pion) (1) - According to $p = BQr$ (1) - The momentum of the proton is larger than the momentum of the pion. (dependent on MP2 or MP1) (1)	Allow proton path is less curved Allow $p \propto r$	3
15(b)(i)	- Converts eV to J (1) - use of $\Delta m = \Delta E / c^2$ (1) - mass = 2.19×10^{-27} (kg) (1)	<u>Example of calculation</u> $m = \frac{1232 \text{ V} \times 1.6 \times 10^{-19} \text{ C} \times 10^6}{(3 \times 10^8)^2 (\text{ms}^{-1})^2}$ $m = 2.19 \times 10^{-27} \text{ kg}$	3



15(b)(ii)	- Calculates mass difference Or states (total) mass of decay products is less than mass of delta particle (1) - According to $\Delta E = \Delta mc^2$ (1) - becomes (extra) E_k (between decay products) (1)	<u>Example of Calculation</u> $939 + 139 = 1078$ $1232 - 1078 = 154(\text{MeV}/c^2)$ Or 1232 is more than 1078(MeV/c^2)	3
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(Total for Question 15 = 14 marks)



Question Number	Acceptable answers	Additional guidance	Mark
16(a)	- See u d s (1) - Comment that charge is zero (1)	If a meson or an incorrect baryon is given which has zero charge, MP2 can be awarded for comment of zero charge.	2
16(b)	- converts eV using 1.6×10^{-19} (1) - divides by c^2 i.e. $(3 \times 10^8)^2$ (1) - mass = 2.0×10^{-27} kg (1)	<u>Example of calculation</u> $m = \frac{1116\text{V} \times 10^6 \times 1.6 \times 10^{-19}\text{C}}{(3 \times 10^8 \text{ m s}^{-1})^2}$ $m = 2.0 \times 10^{-27} \text{ kg}$	3
16(c)	$\Lambda^0 \rightarrow e^+ + e^-$ (no 2) (1) baryon number not conserved (1) $\Lambda^0 \rightarrow n$ only (no 4) (1) momentum or energy cannot be conserved (1) $\Lambda^0 \rightarrow p$ and π^0 (no 5) (1) charge not conserved (1)	More than 3 decays identified as not possible max 2 marks for the decays.	6
16(d)	- Energy of cosmic ray could be turned into matter/mass (1) - According to $\Delta E = c^2 \Delta m$ (1)		2
16(e)	- Neutral particles do not leave a track/ionise (1) - Reference to conservation laws to deduce the properties of particles (1) - Tracks of decay particles can determine momentum of lambda particle (1)		3

(Total for Question 16 = 16 marks)





Question Number	Acceptable answers	Additional guidance	Mark
16(a)	- converts eV to J (1) - use of $\Delta m = \Delta E / c^2$ (1) - mass = 1.9×10^{-28} (kg) (1)	Example of calculation: $m = \frac{106 \text{ V} \times 1.6 \times 10^{-19} \text{ C} \times 10^6}{(3 \times 10^8)^2 (\text{ms}^{-1})^2}$ $m = 1.88 \times 10^{-28} \text{ kg}$	(3)
16(b)(i)	- Charge: $-1 = -1 + 0$ (1) - Baryon number: needs to be stated as 0 (1) - Lepton number: $0 = +1 + (-1)$ (1)		(3)
16(b)(ii)	- Mass difference = 34 (MeV/c²) (1) $E = \Delta mc^2$ so $E = 34 \text{ MeV}$ (1)	alt to $E = \Delta mc^2$ to show unit $\frac{\text{MeV}}{c^2} \times c^2$	(2)
16(b)(iii)	- Mass - energy (1) - Momentum (1)		(2)



Question Number	Acceptable answers	Additional guidance	Mark
18(a)	- it does not leave a track so it is not charged (1) - the charge before the decay is -1 (the pion) and after is -1 (the muon) + 0 (the antineutrino) so it is not charged (1)	Not charged should appear in MP1 or MP2 to get 2 marks	2
18(b)	$\pi^- \rightarrow \mu^- + \bar{\nu}_{(\mu)}$ (1)	Any symbol allowed for the muon	1
18(c)	- Muon is a lepton (1) - Muons / leptons are fundamental particles (1) - Pion is a meson (1) - Pions / mesons consist of a quark and antiquark (1)		4
18(d)	- measures radius (allow between 4 cm and 6 cm) (1) - Use of $p = Bqr$ (1) $B = 1.1 \text{ T}$ (range 0.95 T – 1.42 T) (1) - direction: out of page (1)	Allow use of their measured radius in MP2 <u>Example of calculation:</u> $9.1 \times 10^{-20} \text{ N s} = B \times 1.6 \times 10^{-19} \text{ C} \times 0.52 \text{ m}$ $B = 1.09 \text{ T}$	4



18(e)	• Draws one labelled scaled vector (either pion or muon) • start of muon line should begin at start of pion line Or end of muon line should coincide with end of pion line • angle between them should be approx 30° • p of antineutrino = $9.5 \times 10^{-20} \text{ N s} \pm 0.5 \times 10^{-20} \text{ N s}$ • angle of antineutrino with muon = $150^\circ \pm 5^\circ$ Or angle of antineutrino with pion = $120^\circ \pm 5^\circ$	(1) Label can be “pion” or momentum value. The line should be straight and have an arrow.  (1) (1) (1) (1)	5
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(Total for Question 18 = 16 marks)

Question Number	Acceptable Answers	Additional Guidance	Mark																																
*16 (a)	This question assesses a student's ability to show a coherent and logically structured answer with linkages and fully sustained reasoning. Marks are awarded for indicative content and for how the answer is structured and shows lines of reasoning. The following table shows how the marks should be awarded for indicative content. Indicative content: - the lambda particle is neutral - because it does not leave a track Or two tracks are opposite charged - momentum of proton/ pion can be determined by measuring radius of curve - using $p = Bqr$ - law of conservation of momentum can then be applied - so momentum/energy of the lambda particle can be determined	<table border="1"> <thead> <tr> <th>IC points</th><th>IC mark</th><th>Max linkage mark available</th><th>Max final mark</th></tr> </thead> <tbody> <tr> <td>6</td><td>4</td><td>2</td><td>6</td></tr> <tr> <td>5</td><td>3</td><td>2</td><td>5</td></tr> <tr> <td>4</td><td>3</td><td>1</td><td>4</td></tr> <tr> <td>3</td><td>2</td><td>1</td><td>3</td></tr> <tr> <td>2</td><td>2</td><td>0</td><td>2</td></tr> <tr> <td>1</td><td>1</td><td>0</td><td>1</td></tr> <tr> <td>0</td><td>0</td><td>0</td><td>0</td></tr> </tbody> </table> IC4 – p and r recognisable from the context of the answer IC5 and 6 can be awarded for a labelled momentum vector triangle	IC points	IC mark	Max linkage mark available	Max final mark	6	4	2	6	5	3	2	5	4	3	1	4	3	2	1	3	2	2	0	2	1	1	0	1	0	0	0	0	6
IC points	IC mark	Max linkage mark available	Max final mark																																
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3	2	1	3																																
2	2	0	2																																
1	1	0	1																																
0	0	0	0																																

16 (b)	An explanation that makes reference to the following points: - charge: $0 = +1$ identified as proton (1) -1 identified as pion - Baryon number: $1 = 1$ identified as proton (1) $+ 0$ identified as pion - Lepton number: $0 = 0 + 0$ (1) Or there are no leptons involved		3
16(c)	$(\Lambda^0) \rightarrow p^{(1)} + \pi^{-1}$ (1)		1
16(d)(i)	- Converts eV to J (1) - use of $\Delta m = \Delta E / c^2$ (1) - mass = 1.98×10^{-27} (kg) (1)	<u>Example of calculation</u> $mm = \frac{1115 \text{ V} \times 1.6 \times 10^{-19} \text{ C} \times 10^6}{(3 \times 10^8)^2 (\text{ms}^{-1})^2}$ $mm = 1.98 \times 10^{-27} \text{ kg}$	3
16(d)(ii)	- Converts prefix G to M Or M to G (1) - Determines total energy / mass of lambda before decay (1) - kinetic energy = 4985 MeV (1)	<u>Example of calculation</u> $4.95 \text{ GeV} = 4950 \text{ MeV}$ Total Energy and mass before decay = $4950 + 1115 = 6065 \text{ MeV}$ Total after = $140 + 940 + E_k$ $E_k = 6065 - 1080 = 4985 \text{ MeV}$	3

(Total for Question 16 = 16 marks)



Question Number	Acceptable Answers	Additional guidance	Mark
15a	- fundamental – quarks and leptons (1) - Baryons made of 3 q (1) - Mesons made of quark and antiquark (1)	MP2 and 3 could be given for a named particle and its quark composition	5

Question Number	Acceptable Answers	Additional guidance	Mark
15ciii	0 (1)	zero	1
15d	- High speeds (1) - Or relativistic - Mass (of proton) increases - Or this equation is only valid at non-relativistic speeds (1)	Alt: speeds close to speed of light	2

(Total for Question 15 = 17 marks)

