1 (a) Baryons, mesons and leptons are affected by particle interactions.

Write an account of these interactions. Your account should:

- include the names of the interactions
- identify the groups of particles that are affected by the interaction
- identify the exchange particles involved in the interaction
- give examples of **two** of the interactions you mention.

The quality of your written communication will be assessed in your answer.

(6)

(b) Draw a labelled diagram that represents a particle interaction.

(3)

(Total 9 marks)

2 (a) Complete the table comparing some of the properties of the positive pion, π^+, and the proton.

Name	π^+	**Proton**
Relative charge	+1	
Baryon number		
Quark composition		

(5)

(b) When a positive pion interacts with a proton, a kaon can be produced, along with another strange particle, as shown in this equation

$$\pi^+ + p \rightarrow K^+ + X$$

Circle the type of interaction shown in this equation.

Electromagnetic Gravitational Strong Nuclear Weak Nuclear

(1)

(c) Deduce the relative charge, baryon number and strangeness of particle X.

(3)

(d) Particle X can decay to produce a neutron and positive pion as shown in this equation

$$X \rightarrow n + \pi^+$$

Circle the type of interaction shown in this equation.

Electromagnetic Gravitational Strong Nuclear Weak Nuclear

(1)

(e) Explain your answer.

___

___

___

___

(2)

(f) The neutron and positive pion will then decay. The positive pion can decay into a positron and an electron neutrino.

Write down the equation for the decay of the neutron.

(2)

(g) Explain why no further decays occur.

___

___

___

___

(2)
(Total 16 marks)

3 (a) Name the only stable baryon.

___

(1)

(b) (i) When aluminium-25($^{25}_{13}$Al) decays to magnesium-25 (Mg-25) an electron neutrino (ν_e) and another particle are also emitted.

Complete the equation to show the changes that occur.

$$^{25}_{13}\text{Al} \rightarrow \,^{25}_{\dots\dots}\text{Mg} + \,^{\dots\dots}_{\dots\dots}\dots\dots\dots + \nu_e$$

(2)

(ii) Name the exchange particle responsible for the decay.

___

(1)
(Total 4 marks)

4 Cosmic rays are high-energy particles coming from Space. They collide with the air molecules in the Earth's atmosphere to produce pions and kaons.

(a) Pions and kaons are mesons. Identify the quark–antiquark composition for a meson.

Tick (✓) the correct answer in the right-hand column.

	✓ if correct
qqq	
$q\bar{q}\bar{q}$	
$q\bar{q}$	
qq	

(1)

(b) A positron with a kinetic energy of 2.0 keV collides with an electron at rest, creating two photons that have equal energy.

Show that the energy of each photon is 8.2×10^{-14} J.

(3)

(c) Calculate the wavelength of a photon of energy 8.2×10^{-14} J.

wavelength = ________________________ m

(2)

(d) Show that the speed of the positron before the collision was about 2.7×10^{7} m s^{-1}.

(3)

(e) Calculate the de Broglie wavelength of the positron travelling at a speed of 2.7×10^7 m s^{-1}.

wavelength = ________________________ m

(2)

(f) The separation between the carbon atoms in graphite is about 0.15 nm.

Discuss whether electrons travelling at 2.7×10^7 m s^{-1} can be can be used to demonstrate diffraction as they pass through a sample of graphite.

____

____

____

____

____

____

____

____

____

(4)

(Total 15 marks)

5 Under certain conditions a photon may be converted into an electron and a positron.

(a) State the name of this process.

____

(1)

(b) For the conversion to take place the photon has to have an energy equal to or greater than a certain minimum energy.

(i) Explain why there is a minimum energy.

____

____

(2)

(ii) Show that this minimum energy is about 1 MeV.

(1)

(iii) Explain what happens to the excess energy when the photon energy is greater than the minimum energy.

____

____

(1)

(iv) A photon has an energy of 1.0 MeV.

Calculate the frequency associated with this photon energy.
State an appropriate unit in your answer.

frequency = ___________ unit = ___________

(4)

(Total 9 marks)

6 (a) State what is meant by the specific charge of a nucleus and give an appropriate unit for this quantity.

____

____

____

____

unit: ______________________

(2)

(b) Nucleus X has the same nucleon number as nucleus Y. The specific charge of X is 1.25 times greater than that of Y.

(i) Explain, in terms of protons and neutrons, why the specific charge of X is greater than that of Y.

____

____

____

____

(2)

(ii) Nucleus X is ${}^{10}_{5}\mathrm{B}$. Deduce the number of protons and the number of neutrons in nucleus Y.

number of protons ______________________

number of neutrons ______________________

(4)

(Total 8 marks)

7 Which of the following nuclei has the smallest specific charge?

A	${}^{1}_{1}\mathrm{H}$	☐
B	${}^{12}_{6}\mathrm{C}$	☐
C	${}^{14}_{6}\mathrm{C}$	☐
D	${}^{235}_{92}\mathrm{U}$	☐

(Total 1 mark)

8 $^{232}_{90}Th$ is an unstable nuclide in a radioactive decay series. It decays by emitting an α particle. The next two nuclides in the series emit β^- particles.

What nuclide is formed after these three decays have taken place?

A $^{230}_{90}Th$ ☐

B $^{228}_{92}U$ ☐

C $^{228}_{88}Ra$ ☐

D $^{228}_{90}Th$ ☐

(Total 1 mark)

9 Which line does **not** give the correct exchange particle for the process?

	Process	**Exchange particle**	
A	gravitational attraction	W boson	☐
B	electrostatic repulsion of electrons	virtual photon	☐
C	strong interaction	pion	☐
D	β^- decay	W boson	☐

(Total 1 mark)

10 Which line correctly classifies the particle shown?

	Particle	**Category**	**Quark combination**	
A	neutron	baryon	$\bar{u}d$	☐
B	neutron	meson	udd	☐
C	proton	baryon	uud	☐
D	positive pion	meson	$\bar{u}d$	☐

(Total 1 mark)

11 Which of the following statements about muons is **incorrect**?

A	A muon is a lepton.	○
B	A muon has a greater mass than an electron.	○
C	If a muon and an electron each have the same de Broglie wavelength then they each have the same momentum.	○
D	A muon with the same momentum as an electron has a larger kinetic energy than the electron.	○

(Total 1 mark)

12 What is the best estimate for the order of magnitude for the diameter of an atom?

A	10^{-14} m	○
B	10^{-12} m	○
C	10^{-11} m	○
D	10^{-8} m	○

(Total 1 mark)

Mark schemes

1 (a) **The student's writing should be legible and the spelling, punctuation and grammar should be sufficiently accurate for the meaning to be clear.**

The student's answer will be assessed holistically. The answer will be assigned to one of three levels according to the following criteria.

High Level (Good to excellent): 5 or 6 marks
The information conveyed by the answer is clearly organised, logical and coherent, using appropriate specialist vocabulary correctly. The form and style of writing is appropriate to answer the question.

Student names strong, weak and electromagnetic interactions. Identifies that only hadrons experience the strong interaction but hadrons and leptons experience weak interaction. Charged particles experience electromagnetic interaction. Is able to identify all exchange particles such as gluons, W+ and W- and virtual photons. Gives examples of two of the interactions i.e. electrons repelling, electron capture, beta decay.

Intermediate Level (Modest to adequate): 3 or 4 marks
The information conveyed by the answer may be less well organised and not fully coherent. There is less use of specialist vocabulary, or specialist vocabulary may be used incorrectly. The form and style of writing is less appropriate.

Student names strong, weak and electromagnetic interactions. Identifies that only hadrons experience the strong interaction but hadrons and leptons experience weak interaction. Charged particles experience electromagnetic interaction. Is able to identify some exchange particles such as gluons, W^+ and W^- and virtual photons.

Low Level (Poor to limited): 1 or 2 marks
The information conveyed by the answer is poorly organised and may not be relevant or coherent. There is little correct use of specialist vocabulary. The form and style of writing may be only partly appropriate.

Student names strong, weak and electromagnetic interactions. Identifies that only hadrons experience the strong interaction. Identifies one exchange particle.

The explanation expected in a competent answer should include a coherent selection of the following points concerning the physical principles involved and their consequences in this case.

Names of interactions – strong, weak and electromagnetic
hadrons experience strong
hadrons and leptons experience weak
charged particles experience electromagnetic
identify exchange particles
give examples of various interactions e.g. electron capture
(either weak interaction or electromagnetic or strong interaction)
first mark conservation at left hand junction of charge, baryon and lepton number ✓
second mark conservation at right hand junction of charge, baryon and lepton number ✓
third mark for correct exchange particle ✓

ignore any reference to gravity
ignore any Feynman diagrams electrostatic not allowed as alternative for electromagnetic

Properties of interactions

- *correct exchange particle ($W^{(+/-)}$boson / Z_0 boson, (virtual) photon, gluon / pion) NB sign on W not required*
- *correct group of particles affected (strong: baryons andmesons, weak: baryons, mesons and leptons, electromagnetic: charged particles)*
- *example of the interaction*

Lower band

1 mark – two interactions OR one interaction and one property for that interaction

2 marks – two interactions and one property for one interaction

Middle band

3 marks – two interactions plus two properties

4 marks – two interactions plus minimum of four properties (e.g. 3 props plus 1 OR 2 props plus 2), if three interactions quoted then properties can be spread between the 3 e.g. one property for each (3) plus one additional

Top band

5 marks – 3 interactions plus two properties for each

6 marks – must give first two properties for all three interactions AND correctly state two examples of interactions e.g. electron capture example of weak, strong nuclear responsible for binding protons / neutrons / baryons together

A table may help:

	strong	weak	EM
property 1			
property 2			
property 3			

(b)

if exchange particle not identified but baryon and lepton numbers conserved on both sides − 1 mark
ignore orientation of line showing exchange particle or any arrows on exchange particle line when awarding first two marks

if arrows on incoming and outgoing interacting particles in wrong direction then lose mark

if lines do not meet at a junction lose 1 mark
***with third mark** orientation of exchange particle line must be consistent with exchange particle shown and no arrow required*

if exchange particle line is horizontal (for weak) then must be a correct arrow
arrow overrides slope

3

[9]

2 (a)

1✓

0✓ 1✓

...

ud✓ uud✓

1 mark each

5

(b) Strong nuclear circled✓

1

(c) Charge *1 + 1 = 1 + X* *X = 1*✓

1

Baryon number *0 + 1 = 0 + X* *X = 1*✓

1

Strangeness *0 + 0 = 1 + X* *X = −1*✓

1

Any order

(d) Weak nuclear circled✓

1

(e) Strangeness of X is -1,

First mark is for showing that strangeness changes

The strangeness of the pion and neutron are both zero

1

The strangeness changes from -1 to 0✓

This can only occur in weak interactions. ✓

Second is for stating that this can only happen if the interaction is weak.

1

(f) $\bar{\ }$

First mark is for the proton

1

$n \rightarrow p$ ✓ $+ \beta^{-} + \bar{\nu}_e$ ✓

Second is for the beta minus and antineutrino.

1

(g) The only particles remaining are electrons / positrons and neutrinos / antineutrinos which are stable ✓

1

1

And a proton which is the only stable baryon ✓

1

1

[16]

3 (a) proton

1

(b) (i) β^+ identified even if numbers incorrect or correct numbers for β^+ **and** proton number on Mg correct

β or β^+ identified and all numbers correct

i.e Second mark not awarded if numbers are correct but there is a minus on the β particle

Allow 1 for consistent equation for β^- decay

2

(ii) W^+ (condone W but not W^-)

1

[4]

4 (a) $q\bar{q}$✓

1

(b) Total energy = 2keV + 2 × 511 keV = 1024 keV✓

= 1024 × 1.6 × 10^{-19} = 1.64 × 10^{-13}J✓

Energy of each photon = 1.64 × 10^{-13}/2 = 8.19 × 10^{-14} (J) ✓

First mark for calculating the total energy in keV.

Second mark is for converting correctly into joules.

Third mark is for dividing by two so ecf for incorrect conversion into joules. Student must show at least 3sf.

3

(c) $\lambda = \frac{hc}{E} = \frac{6.63 \times 10^{-34} \times 3 \times 10^{8}}{8.19 \times 10^{-14}}$ ✓

= 2.43 × 10^{-12} (m) ✓

First mark for the correctly rearranged equation or correct values substituted into equation.

Correct answer only scores 2 marks, ecf from 1 ***(b)***

2

(d) E_k= 2 keV = 2000 × 1.6 × 10^{-19} J = 3.2 × 10^{-16}J✓

$v = \sqrt{\frac{2E_k}{m}} = \sqrt{\frac{2 \times 3.2 \times 10^{-16}}{9.11 \times 10^{-31}}}$ ✓

= 2.65 × 10^{7}(m s^{-1}) ✓

First mark for converting KE into joules.

Second mark for rearranging equation correctly or substituting correct values into equation.

Third mark for correct answer, must be to at least 3sf.

3

(e) $\lambda = \frac{h}{mv} = \frac{6.63 \times 10^{-34}}{9.11 \times 10^{-31} \times 2.65 \times 10^{7}}$ ✓

= 2.75 × 10^{-11}(m) ✓

First mark for rearranging equation correctly or substituting correct values into equation.

Second mark for correct answer.

2

(f) Recognition that separation is 1.5×10^{-10} m and compared to 0.28×10^{-10} (ecf)✓

wavelength is about 5 times less than gap width✓

$\sin\theta = \frac{\lambda}{d} = 0.2 \rightarrow \theta \sim 11°$ ✓

yes (diffraction would be observable)✓

Or words to that effect

4

[15]

5 (a) pair production ✓

1

(b) (i) energy of photon needs to provide at least the <u>rest</u> masses ✓

OR at least the <u>rest</u> energy ✓

of the electron <u>and</u> positron / of (both) particles / of particle and antiparticle ✓

Of the electron and positron / of (both) particles of particle and antiparticle ✓

Can't score 2nd mark without having scored 1st

(allow particles or products)

TO on any suggestion of particles have KE

2

(ii) minimum energy = 2 × 0.510999 = 1.021998 (MeV) ✓

must see working

***and** final answer must be at least 3 sf*

allow detailed argument in reverse

0.5 Mev close to 0.511 MeV

Or $E=mc^2$ leading to 1.024875 MeV

Or $2 \times 5.5 \times 10^{-4} \times 931.5 = 1.02$ MeV

1

(iii) (electron / positron have) kinetic energy ✓

thermal energy n/e

Momentum n/e

1

(iv) (attempts to convert energy to joules)

energy = $1.0 \times 10^{6} \times 1.60 \times 10^{-19} = 1.6 \times 10^{-13}$ (J) ✓

Condone power 10 error on MeV

conversion to J

(use of $E = hf$)

Their energy ÷ $6.63 \times 10^{-34} = f$ ✓

Must see subject or their f on answer line consistent with working

$f = 2.4 \times 10^{20}$ ✓ cao

Hz (condone s^{-1}) ✓

Capital H and lower case z (for symbol)

Allow word written as Hertz (h lower case)

4

[9]

6 (a) the ratio of charge to mass of nucleus ✓

C kg^{-1} ✓

2

(b) (i) number of protons and neutrons the same **or** number of neutrons less **or** mass the same ✓

but more protons therefore greater charge ✓

2

(ii) answers add up to 10 ✓

number of protons = 4 ✓

number of neutrons = 10 − 4 = 6 ✓

evidence of correct calculation ✓

eg 5q = 1.25 × ?q

? = 4

4

[8]

7 D

[1]

8 D

[1]

9 A

[1]

10 C

[1]

11 D

[1]

12 C **[1]**

Examiner reports

1 (a) assessed the quality of written communication and it has often proved to be the case that student answers were much more confident than when they are asked to provide an extended answer to a question based on a topic from the electricity part of the specification. Some very good answers were seen with students clearly identifying three interactions. Weaker students did confuse the properties of these interactions and it was not uncommon to see an incorrect exchange boson linked to an interaction, for example the W^+ with the strong interaction. There was a tendency for students to be a little vague when discussing the weak interaction. A common example of this was statements linking the weak interaction to leptons but not hadrons even though examples of interactions involving both of these classes of particles were then given.

The Feynman diagram in (b) generated some good answers with over half the students scoring full marks. The commonest examples seen were electron capture and the repulsion of two electrons.

3 (a) There were many correct answers, the neutron being the most common incorrect response.

(b) (i) This was generally well done and most students were able to score one or both marks.

(ii) Only a fifth of the students identified the W+ particle or W which was an accepted alternative.

5 There was lots of success for the majority of students in this question.

Students failed to gain credit when they did not address the fact that the energy was the minimum energy in part (b)(i). They needed to emphasise that this was the energy required to produce the rest masses of the electron and the positron and that any energy below this was insufficient. Weaker responses attempted an explanation based on the photoelectric effect or suggested that this minimum was greater than the rest masses of the particles produced. Part (b)(ii) was well done with over two thirds of students achieving 4 marks. Mistakes seen were mainly due to inclusion of power of ten errors in converting MeV into joules.

6 Part (a) was answered well and the evidence suggests that specific charge is a topic that is now much better understood. It has often been found in previous papers that explanations which go beyond standard definitions usually produce considerable discrimination.

This was certainly the case in part (b) (i) and it was quite common for less able students to write confused and contradictory answers. A common mistake was to assume that X and Y were isotopes. Some students also thought that the question was about ions rather than nuclei.

Part (b) (ii) produced better responses although the route to a candidate’s final answer was sometimes difficult to follow. A significant number of students gave answers with no working which is bad practice; especially for a question allocated four marks.