Q1.

(a) State what is meant by the Hubble constant.

____

____

(1)

(b) The recessional velocity of a galaxy 8.0×10^8 ly from Earth is measured to be 1.8×10^4 km s^{-1}.

Show that this suggests a value for the Hubble constant of 73 km s^{-1} Mpc^{-1}.

(2)

(c) (i) Using the value for the Hubble constant given in part (b), estimate the age of the Universe.
Give your answer in years.

age of the Universe ____________________ years

(3)

(ii) State **one** assumption that must be made to justify the estimate made in part (i).

____

____

(1)
(Total 7 marks)

Q2.

Evidence to support the Big Bang theory comes from cosmological microwave background radiation and the relative abundance of hydrogen and helium in the Universe.

(a) Explain what is meant by cosmological microwave background radiation and how its existence supports the Big Bang theory.

____

(3)

(b) Explain how the relative abundance of hydrogen and helium supports the Big Bang theory.

(3)

(Total 6 marks)

Q3.

(a) One of the two postulates of Einstein's theory of special relativity is that the speed of light in free space is invariant.

(i) Explain what is meant by this postulate.

(ii) State and explain the other postulate.

(4)

(b) A stationary muon has a rest mass of 1.88×10^{-28} kg and a half-life of 2.2×10^{-6} s.

Calculate

(i) the mass of a muon travelling at 0.996 c, where c is the speed of light in a vacuum,

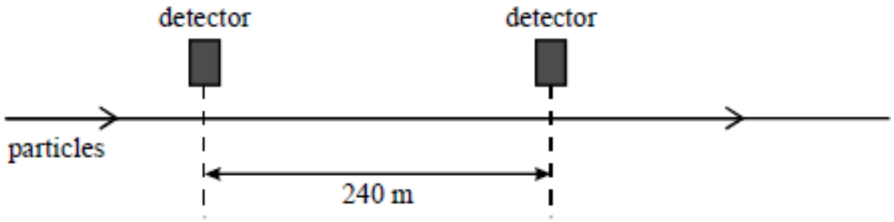
(ii) the distance, in a laboratory frame of reference, travelled in one half-life by a muon moving at 0.996 c.

(6)
(Total 10 marks)

Q4.

(a) In a particle beam experiment, a short pulse of 1 ns duration of particles moving at constant speed passed directly between 2 detectors at a fixed distance apart of 240

m.
The pulse took 0.84 μs to travel from one detector to the other.



(i) Calculate the speed of the particles.

___

___

(ii) Calculate the distance between the two detectors in the frame of reference of the particles.

___

___

___

___

___

___

___

___

(4)

(b) In a 'thought experiment' about relativity, a student stated that a twin who travelled from the Earth to a distant planet and back at a speed close to the speed of light would be the same age on return as the twin who stayed on Earth. Explain why this statement is **not** correct.

___

___

___

___

___

___

___

___

___

(4)

(Total 8 marks)

Q5.

A muon is an unstable particle produced by cosmic rays in the Earth's atmosphere. Muons that are produced at a height of 10.7 km above the Earth's surface, travel at a speed of 0.996c toward Earth, where c is the speed of light. In the frame of reference of the muons, the muons have a half-life of 1.60×10^{-6} s.

(a) (i) Calculate how many muons will reach the Earth's surface for every 1000 that are produced at a height of 10.7 km.

number of muons ____________________

(3)

(ii) Which of the following statements is correct? Tick (✓) the correct answer.

	✓if correct
For an observer in a laboratory on Earth, the distance travelled by a muon that reaches the Earth is greater than the distance travelled by a muon in its frame of reference	
For an observer in a laboratory on Earth, time passes more slowly than it does for a muon in its frame of reference	
For an observer in a laboratory on Earth, the probability of a muon decaying each second is lower than it is for a muon in its frame of reference	

(1)

(b) (i) Show that the total energy of an electron that has been accelerated to a speed of 0.98c is about 4×10^{-13} J.

(2)

(ii) The total energy of an electron travelling at a speed of $0.97c$ is 3.37×10^{-13} J. Calculate the potential difference required to accelerate an electron from a speed of $0.97c$ to a speed of $0.98c$.

potential difference = ____________________ V

(1)

(Total 7 marks)

Q6.

Cosmic rays mostly consist of high-energy protons. These protons can collide with atomic nuclei in the Earth's upper atmosphere producing pions (π^-). Pions are unstable and decay into high-energy muons (μ^-).

(a) (i) Which of the following is the particle group for pions (π^-)?

Tick (✓) the correct answer.

Baryons	☐
Leptons	☐
Mesons	☐
Photons	☐

(1)

(ii) Complete the equation for the decay of a pion (π^-).

$$\pi^- \longrightarrow \mu^- + \underline{\qquad\qquad}$$

(1)

(b) 2.5×10^8 muons are created simultaneously above the EarthÙs surface. These muons are unstable and have a half-life of 2.2 μs. They are created at a height of 10.7 km and travel towards the Earth's surface with a constant vertical velocity of 2.85×10^8 m s^{-1}.

(i) Show that, for the reference frame of an observer on Earth, the time taken for the muons to reach the Earth's surface is approximately 17 muon half-lives.

(2)

(ii) Estimate the number of these muons that an observer on Earth would expect to remain after 17 half-lives.

number ____________________

(2)

(iii) The number of muons that reach the Earth's surface is considerably different from the estimated number in part **(b)(ii)**.

Identify the theory that explains the difference between the estimated and observed number of muons.

____

(1)

(iv) Outline why the number of muons that actually reach the Earth's surface is different from the estimated number in part **(b)(ii)**.

____

____

____

(1)

(v) Calculate, for the reference frame of a muon, the time taken for the muons to travel this distance.

time ____________________ s

(3)

(vi) Calculate the number of muons that remain at the end of the time interval calculated in part **(b)(v)**.

number ____________________

(3)

(Total 14 marks)

Q7.

One of the two postulates of Einstein's theory of special relativity is that the speed of light in free space is invariant.

(a) Explain what is meant by this postulate.

____

____

____

(1)

(b) State the other postulate.

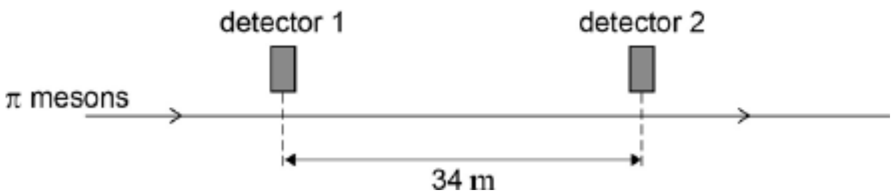
____

____

____

(1)

(c) Two detectors are measured to be 34 m apart by an observer in a stationary frame of reference. A beam of π mesons travel in a straight line at a speed of 0.95 c past the two detectors, as shown in the figure below.



Calculate the time taken, in the frame of reference of the observer, for a π meson to travel between the two detectors.

time = ____________________

(1)

(d) π mesons are unstable and decay with a half-life of 18 ns.

It is found in experiments that approximately 75% of the π mesons that pass the first detector decay before reaching the second detector.

Show how this provides evidence to support the theory of special relativity. In your answer compare the percentage expected by the laboratory observer with and without application of the theory of special relativity.

(5)
(Total 8 marks)

Q8.

Which equation shows the process of annihilation?

A $\pi^- + \pi \longrightarrow \gamma$ ⬭

B $\mathrm{p} + \overline{\mathrm{p}} \rightarrow \gamma + \gamma$ ⬭

C $\beta^- + \mathrm{p} \longrightarrow \gamma$ ⬭

D $\gamma + \gamma \longrightarrow \beta^+ + \beta^-$ ⬭

(Total 1 mark)

Q9.

(i) Calculate the kinetic energy, in J, of a proton accelerated in a straight line from rest through a potential difference of 1.1×10^9 V.

___

___

(ii) Show that the mass of a proton at this energy is 2.2 m_0, where m_0 is the proton rest mass.

___

___

(iii) Hence calculate the speed of a proton of mass 2.2 m_0.

(Total 7 marks)

Q10.

The equation shows an interaction between a proton and a negative kaon that results in the formation of particle, X.

$$K^- + p \rightarrow K^+ + K^0 + X$$

(a) (i) State and explain whether X is a charged particle.

(2)

(ii) State and explain whether X is a lepton, baryon or meson.

(2)

(iii) State the quark structure of the K^-, K^+ and the K^0.

K^-

K^+

K^0

(3)

(iv) Strangeness is conserved in the interaction.

Determine, explaining your answer, the quark structure of X.

(3)
(Total 10 marks)

Q11.

(a) (i) How do hadrons differ from all other subatomic particles?

(ii) Give the quark composition of the following particles.

neutron

neutral pion

(iii) Classify the following as either leptons, baryons or mesons.

kaon

muon

(5)

(b) Which is the most stable baryon?

(1)

(c) This table may be useful in answering the questions which follow.

particle	baryon number	lepton number	strangeness
π^-	0	0	0
p	1	0	0
$\bar{p}$	−1	0	0
e^-	0	1	0
e^+	0	−1	0
$\bar{\nu}_e$	0	−1	0

The particle X, which is a strange particle, decays in the following way:

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

(i) State whether X is a meson, a baryon or a lepton.

____

(ii) Use conservation laws to decide whether each of the following decays of the π^- is possible. Give a reason for your answer.

(A) $\pi^- \rightarrow e^+ + \nu_e$

Is this decay possible? ____

reason ____

(B) $\pi^- \rightarrow \bar{p} + e^- + e^+$

Is this decay possible? ____

reason ____

(5)

(Total 11 marks)

Q12.

(a) *Hadrons* are a group of particles composed of quarks. Hadrons can either be baryons or mesons.

(i) What property defines a hadron?

____

(1)

(ii) What is the quark structure of a baryon?

____

(1)

(iii) What is the quark structure of a meson?

____

(1)

(b) State **one** similarity and **one** difference between a particle and its antiparticle.

similarity ____

____

difference

____

____

(2)

(c) Complete the table below which lists properties of the antiproton.

	charge / C	**baryon number**	**quark structure**
antiproton			

(2)

(d) The K^- is an example of a meson with strangeness –1. The K^- decays in the following way:

$K^- \rightarrow \mu^- + \overline{\nu_\mu}$

(i) State, with a reason, what interaction is responsible for this decay.

____

____

____

____

(2)

(ii) State **two** properties, other than energy and momentum, that are conserved in this decay.

____

____

____

____

(2)

(Total 11 marks)

Q13.

Which line correctly classifies the particle shown?

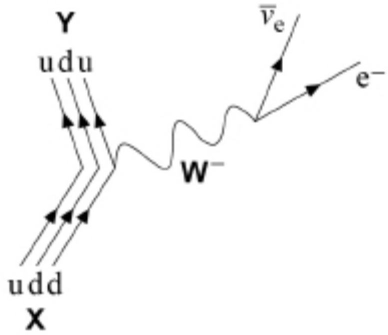
	Particle	**Category**	**Quark combination**	
A	neutron	baryon	$\bar{u}d$	☐
B	neutron	meson	udd	☐
C	proton	baryon	uud	☐
D	positive pion	meson	$\bar{u}d$	☐

(Total 1 mark)

Q14.

The diagram below represents the decay of a particle **X** into a particle **Y** and two other particles.

The quark structure of particles **X** and **Y** are shown in the diagram.



(a) Deduce the name of particle **X**.

____

(1)

(b) State the type of interaction that occurs in this decay.

____

(1)

(c) State the class of particles to which the $\mathbf{W^-}$ belongs.

____

(1)

(d) Show clearly how charge and baryon number are conserved in this interaction.

You should include reference to all the particles, including the quarks, in your answer.

____

____

____

____

____

(2)

(e) Name the only stable baryon.

____

(1)

(f) A muon is an unstable particle.

State the names of the particles that are produced when a muon decays.

(1)
(Total 7 marks)

Mark schemes

Q1.

(a) Gives the ratio of the (recessional) velocity (of galaxies) to distance from Earth

Accept equation with terms defined

not

v depends on d,

the relationship between them, shows the relationship between them

B1
1

(b) *d* changed to Mpc (2.45×10^2)
or 1.8×10^4 / their attempt to convert distance

Or d change to m and v to m s^{-1}

B1

(H=) 73.35 or 73.47 seen to at least 3 sf

B1
2

(c) (i) $T = 1 / H$ or $H = 2.4 \times 10^{-18}$ s seen

e.g. $3.08 \times 10^{-19} / 73$

C1

Value in s calculated (4.2×10^{17})

A1

Correct conversion to years 1.3×10^{10}

Allow their value in s

B1
3

(ii) Universe is expanding at constant / steady rate

B1
1

[7]

Q2.

(a) It is the radiation coming from all parts of the Universe ✓

When the Universe cooled sufficiently for matter and radiation to 'decouple', with the combination of protons and electrons to form neutral atoms ✓

This radiation has been red-shifted into the microwave region as the Universe has expanded ✓

OR

This is (em) radiation from all parts of the Universe, ✓

the spectrum has a peak in the microwave region / corresponds to a temperature of 2.7 K ✓

It can be interpreted as the radiation left over from the Big Bang / the photons having been stretched to longer wavelengths and lower energies ✓

One mark is for stating that CMBR comes from all parts of Universe.

Accept Isotropic.

Condone homogeneous.

Condone same at all points in universe.

Another is for referencing the idea that the radiation has a peak in the microwave region.

The third is for linking it to the Big Bang theory.

Condone "left over heat from Big Bang".

3

(b) (The Big Bang theory suggests that a very brief period of) fusion occurred (when the Universe was very young), resulting in the production of helium from fusing hydrogen. ✓

Fusion stopped as the Universe then expanded and cooled ✓

Resulting in a relative abundance of hydrogen and helium in the ratio of 3:1/ cooled too rapidly for the creation of larger nuclei,

Or suitable relevant observation ✓

One mark is for linking helium production to fusion in the early Universe. This mark can also be awarded for description of proton and neutron creation/ 7:1 ratio

3

[6]

Q3.

(a) (i) speed of light (in free space) independent of motion of source **(1)**
and of motion of observer **(1)**
[*alternative (i)*
speed of light is same in all frames of reference **(1)**]

(ii) laws of physics have same form in all inertial frames **(1)**
inertial frame is one in which Newton's 1st law of motion obeyed **(1)**
laws of physics unchanged in coordinate transformation
from one inertial frame of reference to any other inertial frame **(1)**

(max 4)

(b) (i) $m\left(= m_0\left(1-\frac{v^2}{c^2}\right)^{-\frac{1}{2}}\right) = 1.88 \times 10^{-28}\,(1-(0.996)^2)^{-\frac{1}{2}}$ **(1)**

= 2.10 × 10^{-27} kg **(1)**

(ii) t_0 = 2.2 × 10^{-6} s **(1)**

$t\left(= t_0\left(1-\frac{v^2}{c^2}\right)^{-\frac{1}{2}}\right)$ = 2.2 × 10^{-6} (1 – $(0.996)^2$)$^{-\frac{1}{2}}$ (s) **(1)**

= 2.46 × 10^{-5} (s) **(1)**

s(= vt = 3.00 × 10^8 × 0.996 × 2.46 × 10^{-5}) = 7360 m **(1)**

[*alternative (ii)*
l (= vt = 0.996 × 3.0 × 10^8 × 2.2 × 10^6) = 657 (m) **(1)**

correct substitution of l in $l = l_0\sqrt{1-\frac{v^2}{c^2}}$ **(1)**

$l_0\left(= \frac{l}{\sqrt{1-\frac{v^2}{c^2}}}\right) = \frac{657}{\sqrt{1-0.996^2}}$ **(1)**

l_0 = 7360 m **(1)**

(6)

[10]

Q4.

(a) (i) (use of $v = \frac{d}{t}$ gives) $v = \frac{240}{0.84\times10^{-6}}$ = 2.8(6) × 10^8 m s^{-1} **(1)**

(ii) actual length = 240 m **(1)**

(use of $l = l_0\left(1-\frac{v^2}{c^2}\right)^{1/2}$ gives)

length in particle frame, $l = 240\left(1-\frac{2.86^2}{3^2}\right)^{1/2}$ **(1)**

(allow C.E. for value of v)

l = (240 × 0.30) = 72(.5) m **(1)**

4

(b) time between two events depends on speed of observer

[or $t = t_0\left(1-\frac{v^2}{c^2}\right)^{1/2}$ or rocket time depends on speed of traveller] **(1)**

traveller's journey time is the proper time between start and stop
[or t_0 is the proper time or t is the time on Earth] **(1)**
journey time measured on Earth > journey time measured by traveller
[or $t > t_0$ or rocket time slower / less than Earth time] **(1)**
traveller younger than twin on return to Earth **(1)**

4

[8]

Q5.

(a) (i) Distance travelled in muons' frame of reference
$= 10700(1-0.996^2)^{1/2} = 956$ m ✓
Time taken in muons' frame of reference = 3.2 μs ✓
This is 2 half-lives so number reaching Earth = 250 ✓
OR
Time in Earth frame of reference
$= 10700 / (0.996 \times 3 \times 10^8) = 3.581 \times 10^{-5}$ s ✓
Time taken in muons' frame of reference = 3.2 μs ✓
This is 2 half-lives so number reaching Earth = 250 ✓
OR
Half-life in Earth frame of reference
$= 1.6 \times 10^{-6} / (1-0.996^2)^{1/2} = 17.9 \times 10^{-6}$ s ✓
Time taken $= 35.8 \times 10^{-6}$ s ✓
This is 2 half lives so number reaching Earth = 250 ✓
OR
Distance travelled in muons' frame of reference
$= 10700(1-0.996^2)^{1/2} = 956$ m ✓
Distance the muon travels in one half-life in muons reference frame
$= 0.996 \times 3 \times 10^8 \times 1.6 \times 10^{-6} = 478$ m ✓
Therefore 2 half-lives elapse to travel 956 m so number = 250 ✓
OR
Decay constant in muon frame of reference
Or decay constant in the Earth frame of reference ✓

Uses the corresponding elapsed time and decay constant in
$N = N_0 e^{-\lambda t}$ ✓
Arrives at 250 ✓

All steps in the working must be seen

Award marks according to which route they appear to be taking

The number left must be deduced from the correct time that has elapsed in the frame of reference they are using

3

(ii)

	✓ if correct
For an observer in a laboratory on Earth the distance travelled by a muon is greater than the distance travelled by the muon in its frame of reference	✓

For an observer in a laboratory on Earth time passes more slowly than for a muon in its frame of reference	
For an observer in a laboratory on Earth, the probability of a muon decaying each second is lower than it is for a muon in its frame of reference	

1

(b) (i) Total energy = $9.11 \times 10^{-31} \times (3 \times 10^{8})^{2} / (1\text{-}0.98^{2})^{1/2}$ ✓

4.12×10^{-13} J seen to 2 or more sf ✓

Show that so working must be seen

2

(ii) Change = 7.5×10^{-14} J

V = 469 (470) kV allow ecf using their answer to (i) ✓

ecf is their ((i) −3.37) × 10^{-13}) / 1.6 × 10^{-19}

Using 4 × 10^{-13} gives 394 (390) kV

Using 3.9 × 10^{-13} gives 331(330) kV

Do not allow 1 sf answer

1

[7]

Q6.

(a) (i) Only Box Ticked: Mesons

1

(ii) (Muon) anti−neutrino symbol

Not electron anti−neutrino

Penalise incorrect subscript

1

(b) (i) Use of Speed = distance / time by rearrangement and 3.75×10^{-5} (s) seen

Or

$10.7 \times 10^{3} \div 2.85 \times 10^{8} = 3.75 \times 10^{-5}$ (s) seen

Or substitution **and** 3.75×10^{-5} (s) seen

No. of half-lives = $3.75 \times 10^{-5} \div 2.2 \times 10^{-6}$ = 17.065 or 17.07

not 17.05 not 17.06

At least 3 sf for answer 17.1

$3.75 \times 10^{-5} \div 17$ = 2.208 or 2.21 μs

At least 3 sf

Or

$17 \times 2.2 \times 10^{-6} = 37.4 \times 10^{-5}$ ***with comparison***

2

(ii) $2.5 \times 10^{8} \times (1/2)^{17}$ or equivalent

1900 to 1910 (1910 maximum to 4 sf)

Answer consistent with any working seen

Use of $N = N_0\, e^{-\lambda t}$ and $\lambda = \frac{\ln 2}{2.2 \times 10^{-6}}$ correct sub

Answer in range 1.8×10^3 to 1.91×10^3
(1820 minimum and 1910 maximum to 4 sf)

2

(iii) (Theory of special) relativity

Time dilation / length contraction treat as neutral
Not general relativity

1

(iv)
- Travelling close to speed of light less time passes in muon's reference frame for the journey (so fewer decay)
- Travelling close to speed of light so journey is shorter in length for the muon's frame of reference (so fewer decay)
- Travelling close to speed of light so muons are observed to travel further in a half−life (on Earth) than expected (so fewer decay during journey)
- Travelling close to speed of light so muon's half−life is observed to be longer (on Earth) (so fewer decay)

Allow:

• travelling close to speed of light so time is slower (for muons) so fewer decay

• travelling close to speed of light so time dilates so fewer decay

1

(v) Attempted use of $L = L_o (1-v^2/c^2)^{1/2}$ or $t = t_o/(1-v^2/c^2)^{1/2}$

Correct use of $L = L_o (1-v^2/c^2)^{1/2}$ ***and*** $(t_o = L/v) = 3341/2.85 \times 10^8$

or correctly makes t_o subject of $t = t_o/(1-v^2/c^2)^{1/2}$

$(t_o =)\ 1.17 \times 10^{-5}$ or 1.2×10^{-5} (s)

Condone mix up on L / L_o or t / t_o
1.2×10^{-4} s gets 1 mark
Sub for L_o as 10.7×10^3
Or sub for $t = 3.75 \times 10^{-5}$

3

(vi) Use of $T_{½} = \ln 2/\lambda$ seen with sub for $T_{½}$
allow if seen in partial sub in $N = N_o e^{-\lambda t}$

Use of $N = N_o e^{-\lambda t}$ with $\lambda = 3.15 \times 10^5$ (or equivalent) and t = answer from b(v)

5.7×10^6 to 6.3×10^6
no ecf on answer

Or use of no half−lives = $\frac{b(v)}{2.2 \times 10^{-6}}$

And $\dfrac{2.5 \times 10^8}{2^{\frac{b(v)}{2.2 \times 10^{-6}}}}$

Only accept answers in this range
No ecf on answer

3

[16]

Q7.

(a) speed of light in free space independent of motion of source and / or the observer✓
and of motion of observer

1

(b) laws of physics have the same form in all inertial frames
laws of physics unchanged from one inertial frame to another ✓

1

(c) time taken$\left(= \frac{\text{distance}}{\text{speed}} = \frac{34\text{ m}}{0.95 \times 3.0 \times 10^{8}\text{ m s}^{-1}}\right) = 1.2 \times 10^{-7}$ s✓

1

(d) $t = \frac{18\text{ ns}}{(1 - 0.95^2 c^2 / c^2)^{1/2}}$ ✓

Allow substitution for this mark

1

time taken for π meson to pass from one detector to the other = 58 ns ✓

1

2 half-lives (approximately) in the detectors' frame of reference. ✓

1

two half-lives corresponds to a reduction to 25 % so 75% of the π mesons passing the first detector do not reach the second detector. ✓
OR
Appreciation that in the lab frame of reference the time is about 6 half-lives had passed✓

1

In 6 half-lives 1 / 64 left so about 90% should have decayed✓

Clear conclusion made
Either Using special relativity gives agreement with experiment
or Failure to use relativity gives too many decaying (WTTE)

1

[8]

Q8.

B

[1]

Q9.

(i) E_k (= eV) (= $1.6 \times 10^{-19} \times 1.1 \times 10^{9}$)
= 1.8×10^{-10} (J) **(1)** (1.76×10^{-10} (J))

(ii) (use of $E = mc^2$ gives) $\Delta m = \left(\frac{1.8 \times 10^{-10}}{(3 \times 10^{8})^2}\right) = 2.0 \times 10^{-27}$ (kg) **(1)**

$= \frac{2.0 \times 10^{-27}}{1.67 \times 10^{-27}} m_0 = 1.2 m_0$ **(1)**

(allow C.E. for value of E_k from (i), but not 3rd mark)

$\therefore\ m = m_0 + \Delta m$ **(1)** $(= 2.2\ m_0)$

(iii) (use of $m = m_0 \left(1 - \frac{v^2}{c^2}\right)^{-1/2}$ gives) $2.2 m_0 = \left(1 - \frac{v^2}{c^2}\right)^{-1/2}$ **(1)**

$v = \left(1 - \frac{1}{2.2^2}\right)^{1/2} c$ **(1)**

$= 2.7 \times 10^8$ m s^{-1} **(1)**

[7]

Q10.

(a) (i) X must have a <u>negative charge</u>✓
to conserve charge✓

second mark dependent on first i.e. conserve charge alone scores nothing

can gain second mark by showing balanced equation

2

(ii) X must be a baryon✓
to conserve baryon number✓

here two marks are independent i.e. conserve baryon number alone scores 1 mark

can gain second mark by showing balanced equation

2

(iii) K^-: s $\bar{u}$ OR strange anti-up ✓

K^+: u $\bar{s}$ OR up anti-strange✓

K^0: d $\bar{s}$ OR s$\bar{d}$ OR down anti-strange OR strange anti–down✓

in each case the symbols or words can be in either order

must be a bar over anti – quark
can be upper case letters e.g. U

3

(iv) (strangeness on LHS is -1)
strangeness on RHS without X is +2 / strangeness of X is -3 ✓
thus sss
OR
strangeness on RHS without X is +2 / strangeness of X is -1✓
thus sdd✓✓

correct strangeness without X on RHS is minimum working needed for first mark
next two marks awarded for correct quark structure

3

[10]

Q11.

(a) (i) hadrons (are not fundamental) are composed of quarks
[or hadrons may interact through the strong nuclear force (as well as all the other interactions)] **(1)**

(ii) (neutron) udd **(1)**
(neutral pion) $u\bar{u}$ or $d\bar{d}$ **(1)**

(iii) (kaon) meson **(1)**
(muon) lepton **(1)**

5

(b) proton **(1)**

1

(c) (i) (X) baryon **(1)**

(ii) (a) not possible **(1)**
charge not conserved **(1)**
(allow C.E. from previous line)

(b) not possible **(1)**
baryon number not conserved **(1)**
(allow C.E. from previous line)

5

[11]

Q12.

(a) (i) particles that experience the strong (nuclear) force/interaction **(1)**

1

(ii) particles composed of **three quarks** **(1)**

1

(iii) particles composed of a quark and an antiquark **(1)**

1

(b) similarity: but the same (rest) mass **or** rest energy **(1)**

difference: **opposite** quantum states eg charge **(1)**

2

(c)

	charge/C	baryon number	quark structure
antiproton	-1.6×10^{-19}	–1	$\bar{u}\bar{u}\bar{d}$

–1 for each error

2

(d) (i) weak interaction **(1)**

strange not conserved or there is a change/decay of quark (flavour) **(1)**

2

(ii) **any two**

eg charge

baryon number

(muon) lepton number

2

[11]

Q13.

C

[1]

Q14.

(a) Neutron

Condone misspelling eg nuetron

1

(b) <u>Weak</u> (interaction)

Ignore nuclear or references to beta

1

(c) Bosons

Accept 'exchange particles'
Do not allow 'force mediator'

1

(d) charge number

2/3 -1/3 – 1/3 → 2/3 +-1/3 + 2/3 - 1 + 0 ✓

Ignore equation if given, marking should be based on the numbers

baryon number

1/3 + 1/3 + 1/3 → 1/3 + 1/3 + 1/3 + 0 + 0 ✓

Allow 1 for both correct in terms of n & p instead of quarks:
0 → +1 + -1 + 0
1 → 1 + 0 + 0

2

(e) proton

Allow 'free proton'

1

(f) Electron + an electron antineutrino + muon neutrino

All 3 needed
Condone anti-electron neutrino for electron anti-neutrino
No credit given for symbols

Allow antiparticle answer: positron, electron neutrino, muon antineutrino

1

[7]

Q1.

(a) Only small minority were able to express what is meant by the Hubble constant clearly. Most gave vague answers such as that it gives the relationship between velocity and distance of galaxies.

(b) Here the first requirement was to show the change the distance from ly to Mpc. Those who could do this usually managed the next step without difficulty.

(c) (i) There were many who were unable to make any progress with this calculation. Some clearly had a number for the age of the Universe ($\approx 10^{10}$y) in mind and made an incomprehensible series of calculations to arrive at that number. Converting between units was a problem for many.

(ii) Relatively few candidates gave an acceptable response to this part.

Q2.

This question addressed the general practicalities of making measurements (which was conspicuously poorly-answered in 2017) and use of log graphs to discover power laws.

(a) Two approaches were seen for obtaining the vertical distance y. The indirect approach involved measuring the height of the tape (from the floor) at the free end and subtracting this from the height of the bench. The two measurements involved required the use of a vertical ruler and how this was to be achieved was widely ignored. Examiners were looking for the use of a set-square in contact with the ruler and the floor to make the ruler vertical, a detail that could easily be provided if the students added detail to Figure 7 as was suggested. That so few chose to follow this advice explains why barely 10% were able to score both marks. Another suggested method employed a horizontal reference, established by laying a straight edge along the bench to overhang the free end of the tape. A ruler (made vertical with a set-square) could then measure y directly. Those students taking this route were more prepared to add detail to the diagram, but often showed the straight edge failing to reach the bench or omitted detail involving the set-square. Other approaches, where safe and relevant, could earn credit, such as the use of a plumb line or spirit level. Those who suggested using bits of string, lasers or trigonometry did not gain credit. Disappointingly, nearly half of the students failed to gain any credit for their answer.

(b) Many students identified that y would become very small if x was less than 70 cm but barely 10% correctly stated that this made the percentage uncertainty in y unacceptably high.

(c) All of the marking points discriminated well but not always in combination, so only 10.2% of students scored all three marks. The line quality was usually good, but examiners expected the line to pass above the first and below the sixth points: a surprising number of students drew their line passing through or below the first point. The result of the gradient calculation usually fell within the expected range, but those who truncated it (usually to 4) were penalised. In addition, those who copied their gradient result onto the answer line for n failed to recognise that an integer was expected, so they too failed to score.

(d) About half of the students correctly stated that log A was the (log) y-intercept and many then correctly explained how, having obtained the intercept, they could calculate A. A few spoiled their answer by using base 10 for the first point and base e for the latter, and others, anticipating 02.5, stated that they would use data from Table 2. With a three-mark tariff, it was surprising how few students provided detail of how the intercept could be calculated indirectly, a comparatively easy process to describe if done carefully. Over a third of students scored two marks, but very few (4.3%) scored all three.

(e) The work seen here was sometimes very good and two-thirds of students could at least produce a suitable value for A. The problem for many was identifying the order of magnitude (most simply copied their result for A onto the answer line). To a lesser extent, many struggled to identify the unit, particularly when a non-integer was given for n. For a typical value of A, using the top row in Table 2, a result of 1.99 × 10−7 was routinely obtained. Examiners accepted −7 or 10−7 for the order of magnitude and cm−3 for the unit. A non-integer n such as 3.3 would produce A = 6.09 × 10−6 so the order of magnitude is −5 and the unit cm−2.3. As with question 02.4, all the marking points were accessible, but it was unusual to see all scored together; just less than 10% gained full credit.

Q3.

Most candidates scored at least one mark in part (a)(i). In part (a)(ii) many candidates correctly stated that the laws of physics have the same form in all inertial frames, but few explained correctly what an inertial frame is. A significant number of candidates referred only to Newton's laws instead of the laws of physics.

Many candidates scored both marks in part (b)(i), although some lost marks through failing to square the speed or omitting the unit of mass. In part (b)(ii) many candidates scored full marks by calculating the half-life in the laboratory frame of reference then multiplying by the speed to calculate the correct distance. Candidates who calculated the distance in the muon frame from the speed generally failed to go on to calculate the distance in the laboratory frame correctly. Most candidates who failed to score full marks either confused the proper length and the contracted length, or the proper time and the observed time.

Q4.

In part (a) most candidates correctly calculated the speed of the particles, although a significant number incorrectly interpreted μ as 10^{-3}. Many clear and correct answers were also seen in part (a)(ii) although some candidates failed to score on this calculation because they confused the proper length with the length in the particles’ reference frame.

There were some very clear and correct answers in part (b). These answers demonstrated clarity of thought and the ability to write with coherence and precision. These particular candidates clearly knew how to apply the time dilation formula and in some cases they used their own values in order to amplify what they had already written. Candidates who did not score well often gave contradictory or ambiguous statements, with little or no reference to the time dilation expression.

Q5.

(a) (i) There were a number of ways of tackling this and there were many correct responses. Those who failed did so because they mixed up data for the two frames of reference. For example students often determined the decay constant λ in the muon reference frame and the time of flight t in the reference frame of an observer on the Earth. They then went on to substitute these data in the equation $N = 1000e^{-\lambda t}$.

(ii) Almost half the students identified the correct statement.

(b) (i) A majority of the students completed this successfully applying the formula on the formula sheet. The most common faults were to use $(0.98c)^2$ in the numerator instead of c^2 or to add or subtract $m_o c^2$.

(ii) Almost half were successful in this fairly straightforward question. The two energies needed were given in J in the stems of (i) and this part so all that was required was to subtract these and divide by 1.6×10^{-19}C. Faults included errors doing the subtraction and using the mass of an electron instead of the charge in the determination of the p.

Q6.

Most candidates identified a pion as being a meson in part (a)(i) but considerably fewer were able to complete the decay equation in part (a) (ii). Some candidates paid no heed to conservation of charge and thought that the electron was the missing particle. Most failed to gain marks through stating that it was an electron antineutrino rather than a muon neutrino; this showed a lack of awareness of the details of conservation of lepton number.

Part (b)(ii) was another example of a “show that” question where marks were dropped due to limited communication by candidates. Candidates would do well to follow simple rules when tackling this type of question. Formulae should be quoted and any rearrangement should have a subject. Each step should be shown in the processing of the data and rounding of data should be avoided. Answers should be presented to more significant figures than the answer being worked towards. It is expected that candidates should be able to use their calculators with sufficient skill to avoid unnecessary rounding in determining an answer.

Part (b)(iii) was completed correctly by almost ¾ of candidates. Surprisingly, some candidates demonstrated their lack of mathematical confidence by using an iterative approach when determining the number remaining. This approach often saw candidates losing count and determining the number after 16 or 18 $T_{½}$ instead of the required 17 half- lives.

Part (b)(iv) was a good discriminator with only higher performing candidates able to produce an answer that explained this phenomenon as a relativistic effect. Lower grade candidates often thought that the number remaining was less than expected due to absorption and scattering.

The calculations in parts (b)(v) and (b)(vi) were extremely demanding. Lower performing candidates mixed up the proper time (t_o) with the relative time observed. These candidates achieved an answer of 1.2×10^{-4} instead of the shorter time of 1.17×10^{-5} s. The answer to part (b) (vi) had to be an integer value and candidates carrying forward their answer of 1.2×10^{-4} s lost the final mark in part (b)(vi) as they quoted N as 9.8×10^{-9}.

Q8.

Students generally find most aspects of the particle physics topic fairly straightforward. This question was no exception with 83% of students remembering the need for two gamma photons to be produced. A was the most common distractor, chosen by students who forgot this important point perhaps.

Q9.

Most candidates were able to calculate the kinetic energy of the proton correctly in part (i). Many gave a correct and concise calculation in part (ii), although some candidates produced lengthy calculations as a result of converting into units of atomic mass then into MeV then into joules. In part (iii), a significant number of candidates were unable to calculate the speed after correctly identifying the principles involved in the calculation.

Q10.

The first three parts of this question were well done and students demonstrated that they were familiar with the relevant conservation laws and could also quote the quark structures of the kaons. A minority did lose marks in (a)(i) however, because they did not state the charge of particle X and merely stated that it was charged.

(a)(iv) was much more discriminating and weaker students did not really appreciate that conservation laws were needed to make the deduction and only the strongest students identified that the strangeness of X was either −3 or −1 depending on the quark structure they used for the K^0.

Q11.

This question again showed good discrimination and in particular showed up the weaknesses of the poorer candidates. Part (a) was usually performed well by most candidates whereas part (b) was answered incorrectly by a large majority of candidates. It was a common misconception in the answer to part (b) that the neutron was the most stable baryon.

It was common in part (c) for more than half the available marks to be earned, but often this was due to consequential errors. It was interesting to note that candidates would often work through conservation of lepton number, baryon number and strangeness but failed to consider conservation of charge. Consequently, part (c)(i)(A) was a stumbling block for most candidates.

Q12.

This question was well answered and candidates' responses suggested that the structure of hadrons is well understood. In part (a), less able candidates tended to give specific examples for baryons and mesons rather than their general quark structure. They also stated that the defining property of hadrons was that they were composed of quarks despite the fact that this was stated in the stem of the question.

Responses to part (b) were generally good although some did state that particles and antiparticles had different charges rather than opposite charges.

The table in part (c) did cause a significant proportion of candidates' problems. The most common error was to identify the charge of the antiproton as –1 even though the unit, C, was given in the heading of the table.

Part (d) was answered confidently although a significant proportion of candidates did seem to think that strangeness was conserved in this decay.

Q14.

This question about neutron decay gave students an opportunity to demonstrate their knowledge and understanding of particle physics, a topic that traditionally scores well at A-level. It included several single word responses that were provided correctly by the majority of students.

(a) This was the most accessible question on the paper, with over 90% of students providing the correct answer.

(b) Although this was also correctly answered by the majority of students, there was some confusion concerning the word ‘interaction’, with ‘beta decay’ being a popular incorrect answer. Correct answers that included references to beta decay were credited with the mark.

(c) Most students were familiar with the term ‘boson’ or gave the answer ‘exchange particle’. Other answers appeared to be the random naming of a familiar particle, such as pion, muon, etc.

(d) This question proved to be more challenging with approximately half of the students only receiving one mark for failing to express their answers in terms of quarks. Other common errors included missing out the baryon number of the leptons (0) or the zero charge on the antineutrino. A surprisingly large number of students tried to answer using extended writing rather than using an equation approach such as the one provided in the mark scheme.

(e) This straightforward piece of recall was provided by a large majority of students. There was no particular incorrect answer.

(f) In this question students needed to provide a lot of information for the single mark available. Unsurprisingly, perhaps, this was one of the least accessible questions on the paper. Few students attempted to provide a reasoned answer based on conservation of electron and muon lepton numbers, i.e. conservation of muon lepton number requires a muon neutrino to be produced; conservation of charge suggests an electron is also produced; and conservation of electron lepton number requires the production of an electron antineutrino.