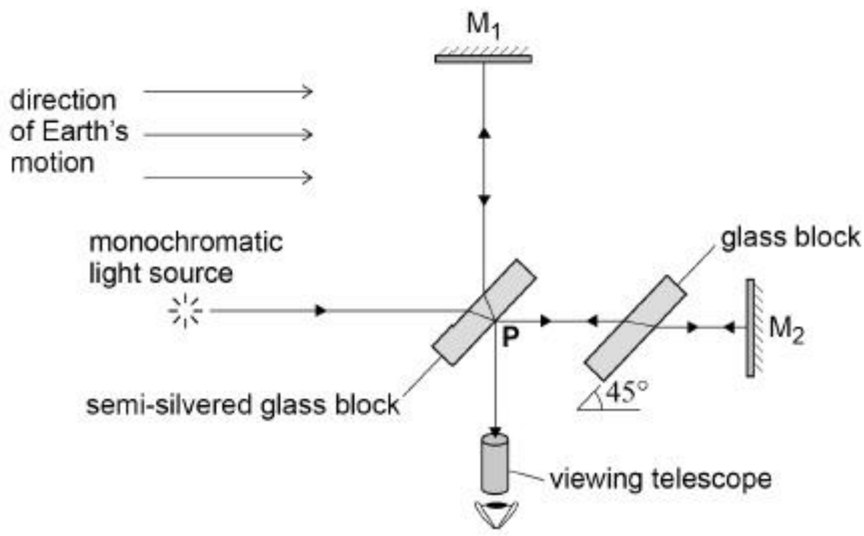
Special relativity

Q1.

Figure 1 shows a diagram of the Michelson-Morley interferometer that was used to try to detect the absolute motion of the Earth through the ether (æther).

Light from the monochromatic source passes through the semi-silvered glass block and takes two different paths to the viewing telescope. The two paths, PM_1 and PM_2, are the same length. Interference fringes are observed through the viewing telescope.

Figure 1



It was predicted that when the interferometer was rotated through 90° the fringe pattern would shift by 0.4 of the fringe spacing.

(a) Explain how the experiment provided a means of testing the idea that the Earth had an absolute motion relative to the ether.

Your answer should include:

- an explanation of why a shift of the fringe pattern was predicted
- a comparison of the results of the experiment to the prediction
- the conclusion about the Earth's absolute motion through the ether.

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(6)

(b) The Michelson-Morley experiment provides evidence for one of the postulates of Einstein’s theory of special relativity.

State this postulate.

(1)

(c) State the other postulate of Einstein’s theory of special relativity.

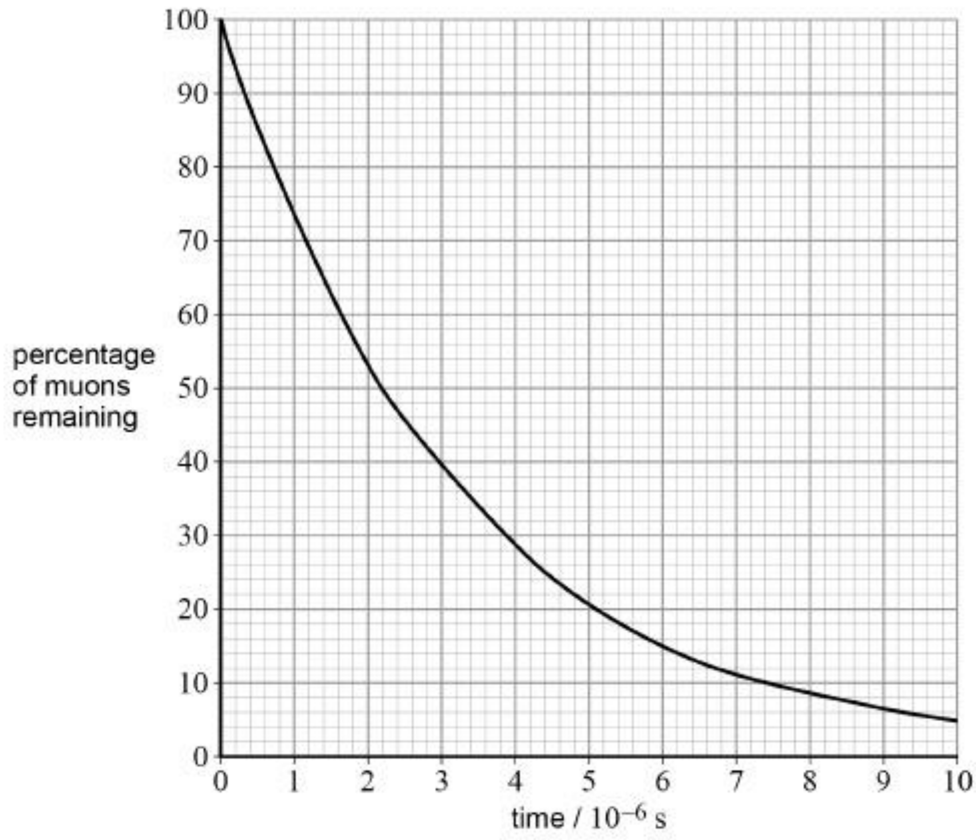
(1)

(d) One consequence of the special theory of relativity is length contraction.

Experimental evidence for length contraction is provided by the decay of muons produced in the atmosphere by cosmic rays.

Figure 2 shows how the percentage of the number of muons remaining in a sample changes with time as measured by an observer in a frame of reference that is stationary relative to the muons.

Figure 2



In a particular experiment, muons moving with a velocity 0.990*c* travel a distance of 1310 m through the atmosphere to a detector.

Determine the percentage of muons that reach the detector.

percentage = ____________________ %

(4)

(Total 12 marks)

Q2.

(a) A student models a spacecraft journey that takes one year. The spacecraft travels directly away from an observer at a speed of 1.2×10^7 m s^{-1}. The student predicts that a clock stationary relative to the observer will record a time several days **longer** than an identical clock on the spacecraft.

Comment on the student's prediction. Support your answer with a time dilation calculation.

____

(4)

(b) In practice, the gravitational field of the Sun affects the motion of the spacecraft and it does not travel directly away from the Earth throughout the journey.

Explain why this means that the theory of special relativity cannot be applied to the journey.

(2)

(Total 6 marks)

Q3.

Cosmic rays detected on a spacecraft are protons with a total energy of 3.7×10^9 eV.

Calculate the velocity of the protons as a fraction of the speed of light.

proton velocity = ____________________ c

(Total 3 marks)

Q4.

(a) Bertozzi's experiment was designed to test the relationship between the kinetic energy of an electron and its speed as predicted by the theory of special relativity.

Describe Bertozzi's experiment.

Your answer should include:

- a diagram of the experimental arrangement
- details of how the kinetic energy and the speed were measured.

(6)

(b) A scientist conducts an experiment similar to Bertozzi's experiment and reports that when the electron speed is 2.93×10^8 m s^{-1} the measured kinetic energy is 2.4 MeV.

Determine whether these data are consistent with the result expected using the theory of special relativity.

(4)

(Total 10 marks)

Q6.

(a) The theory of special relativity is based on two postulates. One of these postulates is that the speed of light in free space is invariant.
State the other postulate.

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(1)

(b) An electron in the Stanford linear accelerator is accelerated to an energy of 24.0 GeV.

(i) An electron travelling with this energy has a velocity v.

Show that the value of $\left(1-\frac{v^2}{c^2}\right)^{\frac{1}{2}}$ is about 2.1×10^{-5}.

(3)

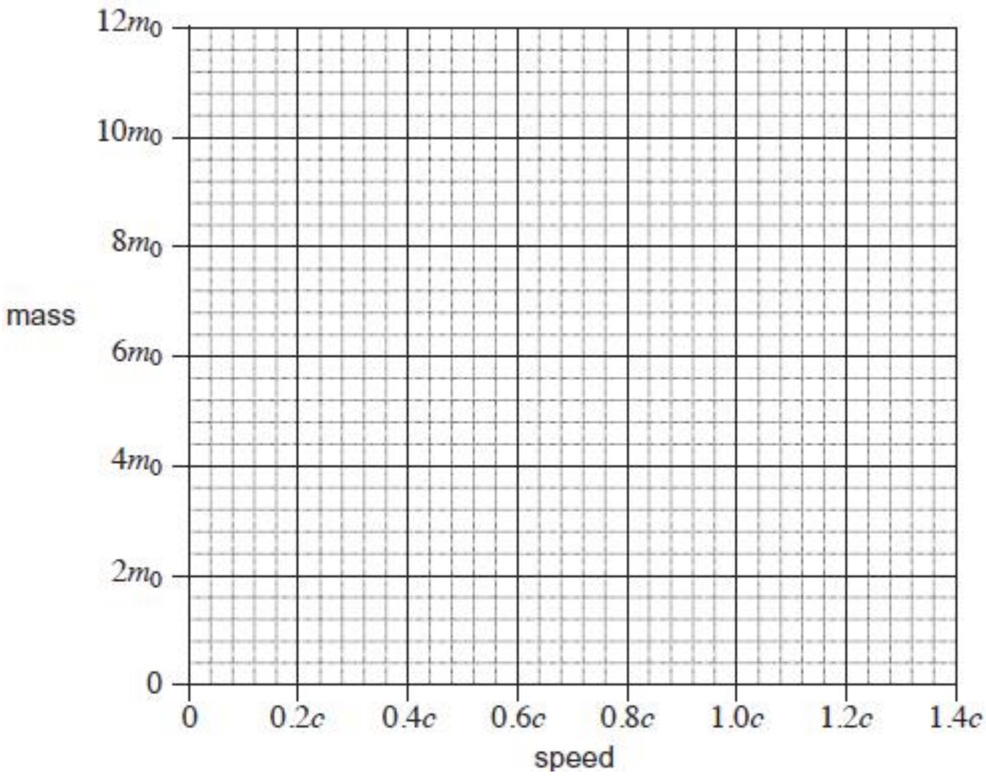
(ii) The Stanford linear accelerator has a length of 3.0 km. Assume that the electron travels for the full length of the accelerator with an energy of 24 GeV.
Calculate the length, in m, of the accelerator in the reference frame of the electron.

length of accelerator = ____________________ m

(1)

(c) Draw a graph to show how the relativistic mass of an electron varies with speed as it is accelerated from rest.

Rest mass of an electron = m_0



(2)
(Total 7 marks)

Q7.

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^-).

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

(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.

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(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)**.

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(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)**.

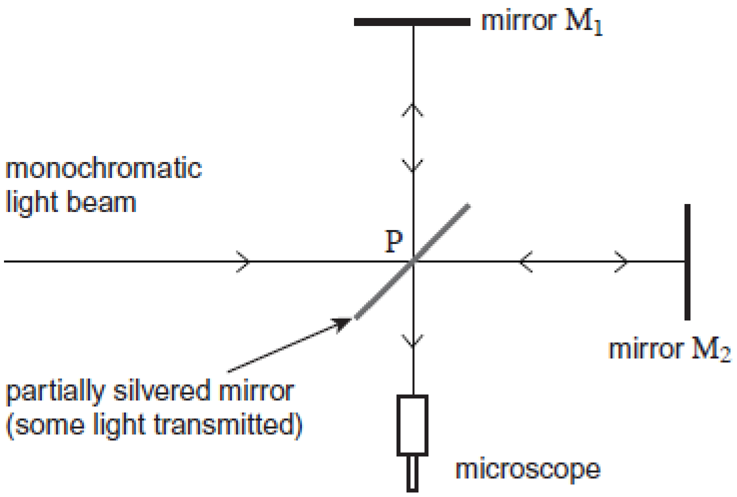
number ____________________

(3)

(Total 14 marks)

Q8.

The diagram shows the paths of light rays through a simplified version of the apparatus used by Michelson and Morley.



In the apparatus, light waves reflected by the mirrors M_1 and M_2, meet at P so that they superpose and produce interference fringes. These are observed using the microscope.

Michelson and Morley predicted that the fringes would shift when the apparatus was rotated through 90°. They thought that this shift would enable them to measure the speed of the Earth through a substance, called the aether, that was thought to fill space.

(a) Explain why Michelson and Morley expected that the fringe positions would shift when the apparatus was rotated through 90°.

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(2)

(b) In their apparatus they made the distances PM_1 and PM_2 the same and equal to d. They used light of wavelength (λ) about 550 nm and knew that the speed of light c was 3.0×10^8 m s^{-1}. Using known astronomical data, they calculated the speed v at which they thought the Earth moved through the aether. They were then able to predict that when the apparatus was rotated through 90° the fringes should shift by a distance $0.4f$, where f was the fringe spacing.

(i) To determine v, Michelson and Morley assumed that the Sun was stationary

with respect to the aether as the Earth moved through it.
Suggest, using this assumption, how the speed v of the Earth through the aether could be determined. You do not need to do the calculation.

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(1)

(ii) Michelson and Morley calculated v to be 3.0×10^4 m s^{-1}.
They worked out Δf, the magnitude of the expected shift of the fringes, using the

formula $\Delta f = \dfrac{2v^2 d}{c^2 \lambda} f$.

Calculate the distance d they used in their experiment.

d = ____________________ m

(1)

(c) Although a shift of 0.4 f was easily detectable, no shift was observed. Explain what this null result demonstrated and its significance for Einstein in his special theory of relativity.

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(2)

(Total 6 marks)

Q9.

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)

Q1.

(a) **The mark scheme gives some guidance as to what statements are expected to be seen in a 1 or 2 mark (L1), 3 or 4 mark (L2) and 5 or 6 mark (L3) answer.**

Level	Criteria	QoWC
6 marks	A thorough and well communicated discussion using most of the statements in bullets 1 2 and 3	The student presents relevant information coherently, employing structure, style and SP&G to render meaning clear. The text is legible.
5 marks	A explanation that includes discussion using most of the statements in bullets 1 , 2 and 3 but may contain minor errors or omissions	
4	The response includes a well presented discussion of two from bullets 1 and two from bullet 3 and one from bullet 2	The student presents relevant information and in a way which assists the communication of meaning. The text is legible. SP&G are sufficiently accurate not to obscure meaning.
3	The response includes a discussion of one comment from each bullet	
2	The response makes comments about two bullet points (This is likely to be from bullets 2 and 3)	The student presents some relevant information in a simple form. The text is usually legible. SP&G allow meaning to be derived although errors are sometimes obstructive.
1	Makes relevant comment from the list	
0	No relevant coverage of the likely statements.	The student's presentation, SP&G seriously obstruct understanding.

The following statements are likely to be present:

Bullet point 1 in question

(Explanation of how shift expected)

1. PM_2 lies in the direction of the Earth's velocity

2. Speed of light different in the two directions

3. The time taken for light to travel from P to M_2 and back to P would be greater than the time taken from P to M_1 and back to P

4. If the speed of light depends on the Earth's velocity through the ether

5. Rotating the apparatus through 90° would cause the time difference to reverse/change

6. When rotated there would be a change in the phase difference between the waves (at each point in the fringe pattern)

Bullet point 2 in the question

(Results compared with prediction)

7. The apparatus was capable of detecting shifts of 0.05 fringe

8. No shift was detected then or in later experiments when apparatus rotated

Bullet point 3 in the question (Conclusions)

9. The experiment showed that there is no absolute motion

10. Ether did not exist so light travels without the need for a material medium

11. The Earth was dragging the ether with it

Many responses fail to demonstrate an understanding that the shift pattern is there in the first place and the shift occurs due to rotation of the apparatus

They often imply that the shift is due to differences in the distance travelled

6

(b) Correct postulate

Invariance of the speed of light <u>in free space/vacuum</u>

Speed of light the same in free space

1

(c) Laws of physics have the same form in all inertial frames

Laws of physics unchanged from one inertial frame to another

The <u>same</u> laws of physics are obeyed/apply/hold in (all) inertial frames of reference/non accelerating frames of reference/frames moving at a constant velocity

Not Allowed

All laws of physics

Laws of physics are the same

Laws of physics are constant...

Mention of Newton's laws being obeyed

Allow 1 here if both (b) and (c) are correct but reversed

1

(d) Time of flight is found to be 4.41×10^{-6} s ✓

$t_o = t\sqrt{1 - \frac{v^2}{c^2}}$ **OR** $t_0 = 4.41 \times 10^{-6}\ \sqrt{1 - 0.99^2}$ ✓

(Proper time t_0 is) 6.22×10^{-7} s ✓

Percentage remaining is (found from the graph) 82 +/– 1

OR

In muon reference frame

$L = 1310\ \sqrt{1 - 0.99^2}$ ✓

185 m✓

$t = \frac{185}{0.99 \times 3 \times 10^8} = 6.23 \times 10^{-7}$ s✓ allow ecf for incorrect length calculation

82 +/– 1%✓

May do

Number of half lives = $6.22 \times 10^{-7}/2.2 \times 10^{-6}$

fraction remaining = $0.5^{0.283} = 0.82$

185 m seen scores 2

Must see this stage with speed = $0.99 \times 3 \times 10^8$

Final answer in range can be awarded even if 0.99 omitted in MP3

Allow minor differences in time (3rd sf) due to rounding in processing

4

[12]

Q2.

(a) (for Proper time, t_0 = 31,536,000 s / 365 days)
Dilated time, t = 31,561,259 s ✓

Time dilation is 25,259 s / 421 minutes / 7.0 hours / 0.29 days ✓

The recorded time will be longer (as predicted) ✓
The recorded time will be less than several days longer (as predicted) ✓

Accept answers in other units (e.g. 365.3 days)

Accept an answer of 31582876 seconds / 365.5 days where a proper time of 365.25 days has been used.

4

(b) Theory of Special Relativity requires no acceleration ✓

(The spacecraft/frame of reference is) accelerating ✓

Alternative answer:

Theory of Special Relativity requires inertial reference frame ✓

(The spacecraft/frame of reference is) not an inertial reference frame ✓

Accept change in direction / speed / velocity as alternatives for accelerating.

2

[6]

Q3.

Conversion of 3.7×10^9 eV to 5.9×10^{-10} J ✓

Accept substitution of $3.7 \times 10^9 \times 1.6 \times 10^{-19}$

Correct use of

$$E = mc^2 = \frac{m_0 c^2}{\left(1 - \frac{v^2}{c^2}\right)^{\frac{1}{2}}}$$

including correct substitution ✓

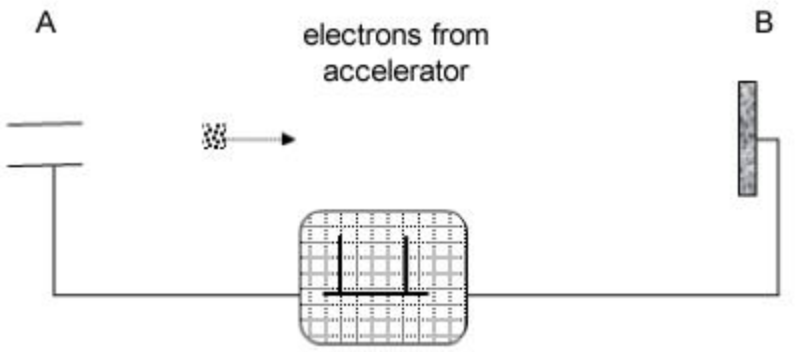
0.97(c) ✓

[3]

Q4.

(a) **The mark scheme gives some guidance as to what statements are expected to be seen in a 1 or 2 mark (L1), 3 or 4 mark (L2) and 5 or 6 mark (L3) answer. Guidance provided in section 3.10 of the *Mark Scheme Instructions* document should be used to assist marking this question.**

L3 5-6 marks	Candidate will draw a useful diagram, and give a coherent well-structured attempt at explaining how energy and velocity are measured with some equations and the use made of the measurements.	The student presents relevant information coherently, employing structure, style and sp & g to render meaning clear. The text is legible.
L2 3-4 marks	The response explains that velocity and kinetic energy were measured and attempts to explain the method used but lacks detail in one or both aspects. The response should show some attempt to structure the account.	The student presents relevant information and in a way which assists the communication of meaning. The text is legible. Sp & g are sufficiently accurate not to obscure meaning.
L1 1-2 marks	The response explains that velocity and kinetic energy were measured but gives little or no significant detail. The account may lack structure.	The student presents some relevant information in a simple form. The text is usually legible. Sp & g allow meaning to be derived although errors are sometimes obstructive.
0 marks	Little or no discussion of relevant content.	The student's presentation, spelling, punctuation and grammar seriously obstruct understanding.



The following statements could be present:
useful diagram
pulses of electrons produced in an accelerator
electron beam detected as it passes A and B
time of flight measured with oscilloscope
velocity = AB / time
each pulse of electrons raises temperature of aluminium plate
temperature rise of plate measured
energy landing on plate $mc\Delta\theta$
energy of electron = $mc\Delta\theta/n$ (n = number of electrons hitting the plate)
e and v measured for different electron energies
compared with prediction from relativity.

6

(b) Ke measured = 2.4 MeV = $2.4\times10^{6}\times1.6\times10^{-19} = 3.84\times10^{-13}$ J✓
Ke predicted = 2.99×10^{13}✓
Difference = 0.85×10^{-13} J✓
% difference = 28% on predicted / 22% on measured✓

or

Calculation of Ke predicted in J as shown above.✓✓
Conversion of energy to MeV.✓
Measured energy is higher than that predicted by more than experimental error can justify (about 28%).✓

4

[10]

Q6.

(a) The laws of physics are the <u>same</u> in <u>all inertial</u> frames of reference OWTTE
Allow specified laws eg Newton's laws applies in all inertial frames of reference
Do not allow laws of physics are ***obeyed or apply***
Allow any / every inertial frame of reference

1

(b) (i) Converts 24 GeV to J $24 \times 10^{9} \times 1.6 \times 10^{-19}$ or 3.84×10^{-9} (J) seen ✓

3.84×10^{-9} or 24×10^{9} = $\frac{9.11\times10^{-31}\times(3\times10^{8})^{2}}{\gamma}(-9.11\times10^{-31}\times(3\times10^{8})^{2})$ ✓

2.14 or 2.13×10^{-5} ✓ from correct working
at least 3 sf needed

Many convert to equivalent mass

4.27×10^{-26} and then work in masses throughout

May include the bracketed term. Depending on whether they assume 24 GeV to be the total energy or the kinetic energy

Allow incorrect powers of 10

May use given γ and find energy and compare with 24 GeV

3

(ii) $3000 \times 2.1 \times 10^{-5} = 0.063$ or 0.064 m ✓

1

(c) Starts at m_o ✓

Shallow increase to

- no more than $2m_o$ at 0.7*c*
- curves (sharply) upwards becoming greater than 0.9*c* at $6m_o$
- never greater than 1.0 *c*
- within ½ square of 1.0*c* at $12m_o$ ✓

Never greater than 1.0c

Allow statement of asymptote

2

[7]

Q7.

(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 =) 1.17×10^{-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]

Q8.

(a) They expected the time taken for the light to travel in one direction to be different from the other ✓

or

Expected light to travel at different speeds in the two directions

However expressed e.g. in terms of the different times taken parallel and at right angles to the Earth's motion (through the Aether)

There would be a phase shift / change in the phase relationship

Not

longer / different paths

or

path difference

2

(b) (i) Speed through aether

$$= \frac{\text{circumference of Earth orbit around the Sun}}{\text{time for one orbit (1 year)}}$$

Need to be clear about the distance and time

or $v = (GM / r)^{1/2}$ with M and r defined

Watch out for confusion between Earth's orbit around the Sun and Earth's rotation on its axis

1

(ii) 11 m

1

(c) Experiment showed speed of light from moving object is same as that from stationary object or

Speed of light in direction of motion is same as in perpendicular direction or

Speed of light does not depend on speed of source or observer

Speed of light being invariant

or

Aether theory incorrect / no aether / no absolute motion

Allow is always 3×10^8 m s^{-1} in air or vacuum instead of invariant

It was a postulate / assumption of the theory of special relativity

Or this supports the theory ✓

Second mark is for e<u>xplicitly</u> linking the observation to Einstein's theory

2

[6]

Q9.

(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 = 35.8×10^{-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 = $9.11 \times 10^{-31} \times (3 \times 10^8)^2 / (1-0.98^2)^{1/2}$ ✓

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]

Q1.

(a) Students needed to demonstrate a clear understanding of the prediction, the experiment itself and the conclusions, as outlined in the bullet points in the question. Even the better students rarely addressed the first bullet point in the question with any conviction, so were limited to a mark in the middle level. Many responses showed only a superficial understanding of the experiment, with many appreciating no more than that rotating the apparatus was expected to produce a fringe shift and as there wasn't one, there is no ether.

Those who had more knowledge of the experiment itself often failed to provide adequate detail in their responses, particularly the detail relating to anticipated effect of the ether, the change in times of travel for the light waves, and the expected changes in phase difference when the apparatus was rotated. Responses from many students indicated a lack of understanding of how fringes were formed and no appreciation that there would be fringes seen whatever the orientation of the apparatus.

(b) Those who failed to gain the mark (72% of students) usually did not state the speed invariant *in free* space.

(c) Approximately 30% gave an acceptable form of the other postulate.

(d) This was answered well, with just over 50% of students gaining three or four marks. Both approaches attracted roughly equal numbers of students. A read-off from the graph was adequate for the final step, but many did correct but unnecessary calculations of the number left. There was a significant minority of students who gave the number that decayed as their final answer having correctly determined the number remaining.

Q2.

(a) A significant number of answers to this question scored full marks. Some students neglected the instruction to support their answer with a time-dilation calculation. In addition, where students' strategy was sound but marks were lost, this tended to be for not fully answering the question which required a judgement on both aspects of the student's prediction, i.e. the time being longer and the magnitude of several days.

(b) The answers given often showed a sound level of knowledge and understanding. Many students identified that the spacecraft would be accelerating, and a requirement of Special Relativity is that the frames of reference are not accelerating. Other students who scored full credit stated that the spacecraft is not an inertial frame of reference, and inertial reference frames are a requirement for Special Relativity. A commonly seen answer that scored partial credit explained what an inertial reference frame was, but did not go on to explicitly state that this was a requirement for the application of Special Relativity.

Q3.

Nearly all students were able to convert the energy given in eV into J. A good number of students went on to complete the calculation successfully. A common error was the incorrect use of the $E_K = mc^2 - m_oc^2$ equation.

Q6.

(a) Appreciation of the postulates is fundamental to special relativity and this needed to be recalled unambiguously to gain the mark.

(b) (i) Many students completed this part successfully. Many however did not show all the steps needed to arrive at a value consistent with that given in the question. Show that questions are common in all physics papers so that students have a value to work with in subsequent parts. In such question all steps in the working must be shown. It has to be clear what equations are used and all data should be substituted. To demonstrate that the final answer is consistent with the value given in the question, the final answer from the calculator should be given to at least 1 more significant figure that the given value. As they were not told otherwise, students could assume that the 24 GeV was the total energy or the kinetic energy. A common error was to use non-relativistic equation ½ $mv^2 = eV$ to calculate v and then calculate the value using the bracketed term given in the question.

(ii) There was a high proportion of correct answers to this part. Incorrect powers of 10 was the most common reason for mistakes in this part. A few used the mass increase equation rather the length contraction equation, actually quoting m = etc.

(c) There were many very good representations of the expected curve with some better responses calculating values and plotting them accurately. However, the criteria for acceptability were chosen so that less than perfect graphs that bore reasonable resemblance to the true curve could gain full credit. It was surprising how many missed the easy mark and identified the electron as having no mass when it was stationary.

Q7.

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_0) 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.

(a) Most students found this hard to explain. A good proportion of the students had some idea of expected difference in speeds of light for light that is transmitted in the direction of the earth's motion through the Aether and perpendicular to it although this was often poorly expressed. Approximately a fifth of the students was able to make further progress and explain how rotating the apparatus would produce a change in the relative phases of waves and produced a shift in the fringe pattern.

(b) (i) There were clues as to how this could be done in the short passage and the stem of the question. It required recognition that the speed required was the orbital speed of the Earth around the Sun. It was completed successfully by a relatively small proportion of the students. Some spoiled their attempt by suggesting calculation of the circumference of orbit using the distance of the Earth from the Sun but then suggesting the orbital period was one day!

(ii) This was a straightforward calculation requiring substitution of appropriate data, all of which was given in the question. About two thirds of the students did it successfully.

(c) This was well done a vast majority stated one conclusion from the experiment and many of these were able to state the significance.

Q9.

(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.