0 1 . 1 A student models a spacecraft journey that takes one year. The spacecraft travels directly away from an observer at a speed of $1.2 \times 10^7 \text{ m s}^{-1}$. 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 marks]

0 1 . 2 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 marks]

6

Question	Answers	Additional Comments/Guidelines	Mark
01.1	(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
01.2	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
Total			**6**

0 2 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.

[3 marks]

proton velocity = _____ c

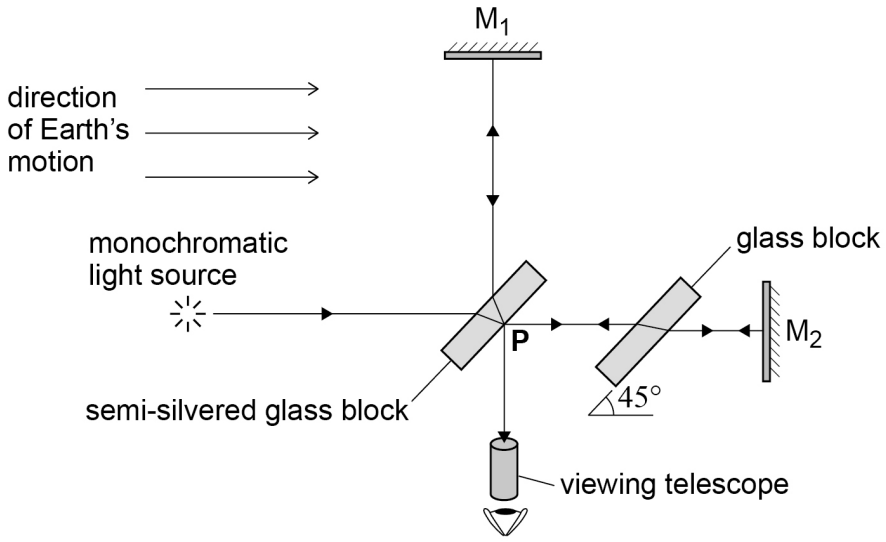
3

Question	Answers	Additional Comments/Guidelines	Mark
02	Conversion of 3.7 x 10^9 eV to 5.9 x 10^{-10} J✓ Correct use of $E = m c^2 = \frac{m_0 c^2}{\left(1 - \frac{v^2}{c^2}\right)^{\frac{1}{2}}}$ including correct substitution ✓ 0.97(c) ✓	Accept substitution of 3.7 x 10^9 x 1.6 x 10^{-19}	3
Total			**3**

0 3 **Figure 6** 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 6



It was predicted that when the interferometer was rotated through 90^{o} the fringe pattern would shift by 0.4 of the fringe spacing.

0 3 . 1 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.

[6 marks]

Extra space is available on the next page

0 3 . 2 The Michelson-Morley experiment provides evidence for one of the postulates of Einstein's theory of special relativity.

State this postulate.

[1 mark]

0 3 . 3 State the other postulate of Einstein's theory of special relativity.

[1 mark]

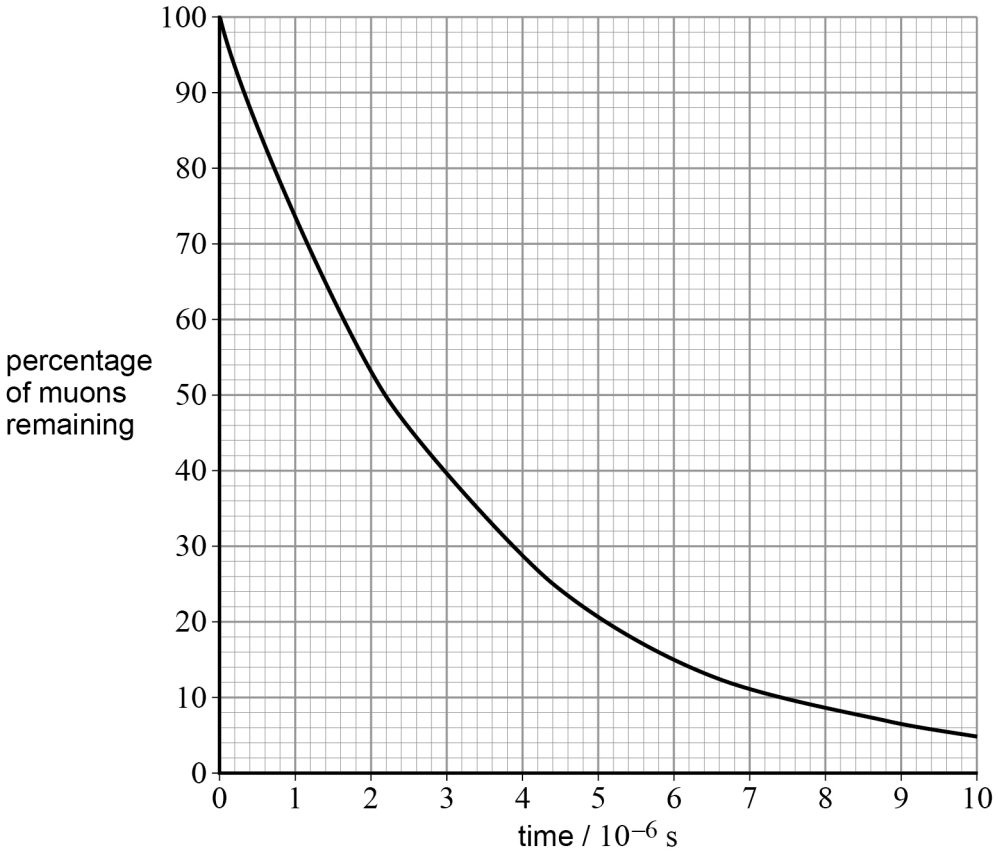
Question 4 continues on the next page

0 3 . 4 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 7 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 7



In a particular experiment, muons moving with a velocity $0.990c$ travel a distance of $1310\ \text{m}$ through the atmosphere to a detector.

Determine the percentage of muons that reach the detector.

[4 marks]

percentage = _____ %

12

END OF QUESTIONS

<table>
<tr><th>Question</th><th>Answers</th><th>Additional Comments/Guidance</th><th>Mark</th></tr>
<tr>
<td>03.1</td>
<td>
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 in marking this question.
<table>
<tr><th>Mark</th><th>Criteria</th><th>QoWC</th></tr>
<tr><td>6</td><td><u>A thorough and well communicated</u>
discussion using most of the statements in bullets 1 2 and 3</td><td rowspan="2">The student presents relevant information coherently, employing structure, style and SP&G to render meaning clear. The text is legible.</td></tr>
<tr><td>5</td><td><u>A explanation that includes</u>
discussion using most of the statements in bullets 1 , 2 and 3 but may contain minor errors or omissions</td></tr>
</table>
</td>
<td>
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.
</td>
<td>6</td>
</tr>
</table>

	4	<u>The response includes a well presented</u> 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.		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	
	3	<u>The response includes a</u> discussion of one comment from each bullet				

	2	<u>The response</u> 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.			

Question	Answers	Additional Comments/Guidance	Mark
03.2	Correct postulate invariance of the speed of light <u>in free space/vacuum</u>. speed of light the same in free space		1
03.3	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 4.2 and 4.3 are correct but reversed	1

03.4	Time of flight is found to be 4.41×10^{-6} s ✓ $t_o = t\sqrt{1-\frac{v^2}{c^2}}$ or $t_o = 4.41 \times 10^{-6}\sqrt{1-0.99^2}$ ✓ (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 x 10^{-7}/2.2 x 10^{-6} fraction remaining = $0.5^{0.283}$=0.82 185 m seen scores 2 <u>Must see this stage with speed = 0.99 x 3 x 10^8</u> Final answer in range can be awarded even if 0.99 omitted in MP3 Allow <u>minor</u> differences in time (3rd sf) due to rounding in processing	4
Total			**12**

0 4 **Table 1** shows data of speed v and kinetic energy E_k for electrons from a modern version of the Bertozzi experiment.

Table 1

v / 10^8 m s^{-1}	E_k / MeV
2.60	0.5
2.73	0.7
2.88	1.3
2.96	2.6
2.99	5.8

0 4 . 1 Classical mechanics predicts that $E_k \propto v^2$.

Deduce whether the data in **Table 1** are consistent with this prediction.

[2 marks]

Do not write outside the box

0 4 . 2 Discuss how Einstein's theory of special relativity explains the data in **Table 1**.

[4 marks]

0 4 . 3 Calculate, in J, the kinetic energy of one electron travelling at a speed of $0.95c$.

[3 marks]

kinetic energy = _____ J

9

END OF QUESTIONS

Question	Answers	Additional Comments/Guidance	Mark	ID details
04.1	Calculation of constant of proportionality for at least two data sets ✓ Allow conversion to J Calculation of at least three data sets and conclusion to the effect that as the constants differ, the classical prediction is not true ✓	Alternative methods of calculation: Calculation of constant of proportionality and then using to calculate other E, v, v^2 and comparing with table. Checking ratio of $\frac{E_m}{E_n} \neq \frac{v_m^2}{v_n^2}$ 1 mark for any calculation that shows KE ≠ $1/2mv^2$ ✓ If more than 3 calculations shown, reward any three correct	2	AO2 1h AO3 1b

Question	Answers	Additional Comments/Guidance	Mark	ID details
04.2	v has upper limit as Ek increases✓ Explanation: As v increase mass increases✓ As v approaches c, mass approaches infinity/increase in mass significant✓ Near c, increases in Ek are due to increase in mass/Ek tends to infinity✓	For MP1 allow comment on their calculations from 4.1 e.g. Ek/v2 increases Do not reward references to 'constant increases' Treat 'exponentially' as neutral Condone energy/total energy for Ek	4	AO3 1b
04.3	$E_0 = m_0c^2 = 8.2 \times 10^{-14}$ J $E = \frac{m_0c^2}{\left(1-\frac{v^2}{c^2}\right)^{\frac{1}{2}}} = 2.6 \times 10^{-13}$ J ✓ $E_k\ (= E - E_0) = 2.6 \times 10^{-13} - 8.2 \times 10^{-14}$ ✓ 1.8×10^{-13} J ✓	If no marks are scored 1 mark can be given for *seeing* 8.2×10^{-14} J Allow ecf from MP1 for incorrect m_o eg use of proton Give all 3 marks for correct answer	3	2 × AO1 1a 1 × AO2 1c
Total			**9**	

0 5 . 1 A muon travels at a speed of $0.95c$ relative to an observer.

The muon travels a distance of 2.5×10^3 m between two points in the frame of reference of the observer.

Calculate the distance between these two points in the frame of reference of the muon.

[2 marks]

distance = _____ m

0 5 . 2 Measurements of muons created by cosmic rays can be used to demonstrate relativistic time dilation.

State the measurements made and the observation that provides evidence for relativistic time dilation.

[2 marks]

Do not write outside the box

0 5 . 3 As the muons travel through the atmosphere, their speeds are reduced by interaction with the particles in the air.

Discuss, with reference to relativity, the effect that this reduction of speed has on the rate of detection of the muons on the surface of the Earth.

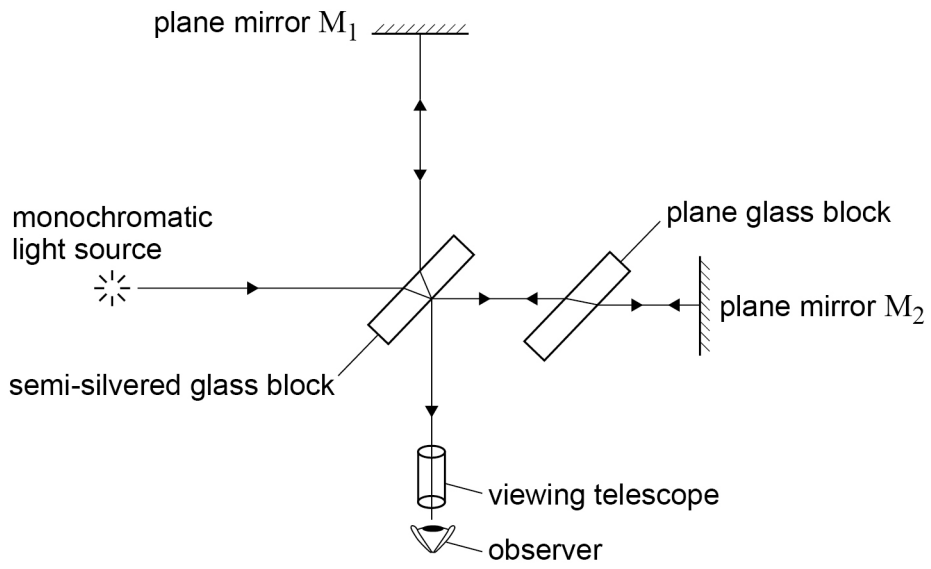
[3 marks]

7

Question	Answers	Additional Comments/Guidance	Mark	ID details
05.1	Lo = 2500 m Length = 2500 x (1 -0.95^2)^{½} ✓ length = 781 (780) m✓		2	AO2.1f
05.2	Number of muons passing through detector per second measured at top of mountain/in upper atmosphere AND Number of muons passing through detector per second measured on ground. ✓ Measurements show far fewer muons decay than expected in time taken (in observer's frame of reference) for muons to travel from upper atmosphere to ground (as the clock in muons frame of ref runs slower than observer so half-life appears longer). ✓	Allow "intensity of muons" Allow number decayed/difference in numbers at upper atmosphere and ground Allow more muons reach the ground than expected	2	AO1a
05.3	Lower velocity means Take longer to travel to ground (in either frame of reference)✓ And time dilation effect less (in Earth frame of reference)/length contraction effect less (in muon frame of reference) (as not so close to c) ✓ More muons decay before reaching ground so rate of detection reduced✓	If there is no reference to frame of reference or relativistic effects award Max 1. Answer needs to be consistent with the implicit frame of reference being discussed	3	AO3.1a
Total			**7**	

0 6 **Figure 5** shows the features of a Michelson-Morley interferometer.

Figure 5



Explain how, using this arrangement, Michelson and Morley attempted to detect the absolute motion of the Earth.

In your answer you should:

- outline the experimental procedure
- explain the expected result of the experiment
- describe the actual result and explain the significance of this result.

[6 marks]

<table>
<tr><th>Question</th><th>Answers</th><th>Additional comments/Guidance</th><th>Mark</th><th>AO</th></tr>
<tr><td>06</td><td>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 in marking this question.
<table>
<tr><td>Mark</td><td>Criteria</td></tr>
<tr><td>6</td><td>All three areas covered with at least two aspects covered in some detail.
6 marks can be awarded even if there is an error and/or parts of one aspect missing.</td></tr>
<tr><td>5</td><td>A fair attempt to analyse all three areas. If there are several errors or missing parts then 5 marks should be awarded.</td></tr>
<tr><td>4</td><td>Two areas successfully discussed, or one discussed and two others covered partially. Whilst there will be gaps, there should only be an occasional error.</td></tr>
<tr><td>3</td><td>One area discussed and one discussed partially, or all three covered partially. There are likely to be several errors and omissions in the discussion.</td></tr>
<tr><td>2</td><td>Only one area discussed, or makes a partial attempt at two areas.</td></tr>
<tr><td>1</td><td>None of the three areas covered without significant error.</td></tr>
<tr><td>0</td><td>No relevant analysis.</td></tr>
</table></td><td>The following statements are likely to be present.
A – outline of experimental procedure
Semi-silvered glass block splits the beam of monochromatic light into two beams
(The plane block ensures that both beams pass through the same thickness of glass and air)
(Beams travel at right angles, to M_1 and M_2 , and return to) combine at telescope with a path difference
Observer sees interference pattern from two beams
Apparatus rotated 90 degrees and pattern observed
B – expected result
Pattern would shift
As path length/speed of light different depending on (orientation relative to) motion of apparatus
So ether exists/absolute motion of Earth detected
C – actual result and significance
No shift in pattern
No evidence of ether
Speed of light is invariant/all motion is relative/no absolute motion</td><td>6</td><td>AO1.1a
× 6</td></tr>
<tr><td>Total</td><td></td><td></td><td>6</td><td></td></tr>
</table>

0 7 . 1 State what is meant by an inertial frame of reference.

[1 mark]

0 7 . 2 A pair of detectors is set up to measure the intensity of a parallel beam of unstable particles.
In the reference frame of the laboratory, the detectors are separated by a distance of $45\ \text{m}$. The speed of the particles in the beam is $0.97c$.

The intensity of the beam at the second detector is 12.5% of the intensity at the first detector.

Calculate the half-life of the particles in the reference frame in which they are at rest.

[4 marks]

half-life = _____ s

0 7 . 3 In calculations involving time dilation, it is important to identify proper time.

Identify the proper time in the calculation in Question **04.2**.

[1 mark]

6

END OF QUESTIONS

Question	Answers	Additional comments/Guidance	Mark	AO
07.1	One which moves at constant velocity	Allow: a reference frame in which Newton's laws / Newton's first law holds.	1	AO1.1a

Question	Answers	Additional comments/Guidance	Mark	AO
07.2	In frame of particle beam Distance between detectors = $45\sqrt{1-\frac{(0.97c)^2}{c^2}} = 10.9$ m ✓ Time = $10.9 / 0.97c = 3.8 \times 10^{-8}$ s ✓ Half-life = time/3 ✓ = 1.3×10^{-8} s ✓	MP1 is for determination of distance between detectors in ref frame of particles MP2 is for determining the time between detectors in the ref frame of particles MP3 is for use of reduction to 12.5% is equivalent to 3 half-lives MP4 is for correct final answer Allow alternative route from ref frame of detectors	4	AO2.1f

Question	Answers	Additional comments/Guidance	Mark	AO
07.3	The time taken for particle beam to travel between detectors 'measured' in the reference frame of particle beam✓	Accept: shortest observable time for a particle passing between detectors. Accept 3.8×10^{-8} s	1	AO2.1e
Total			**6**	

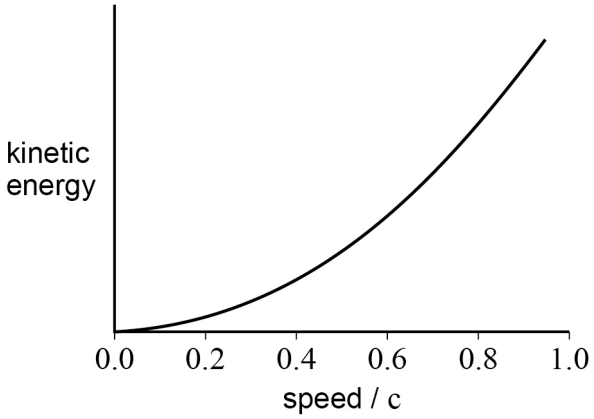
Do not write outside the box

0 8 . 1 Bertozzi investigated how the kinetic energy of electrons varies with speed.

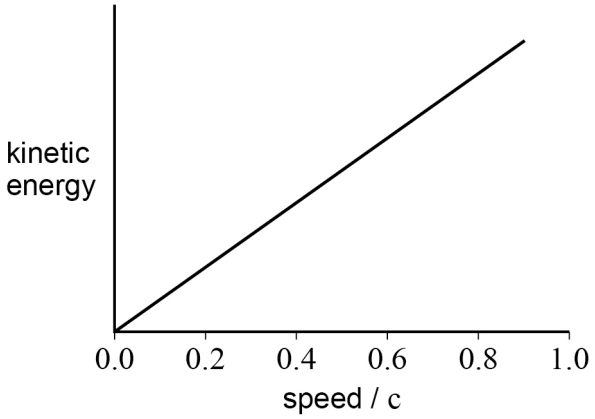
Which graph shows the variation of kinetic energy with speed?
Tick (✓) **one** box.

[1 mark]

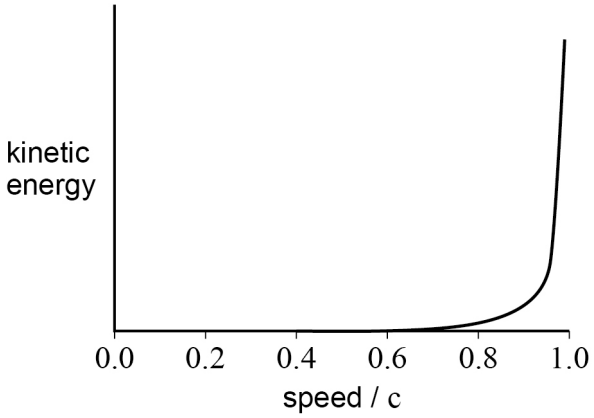
A



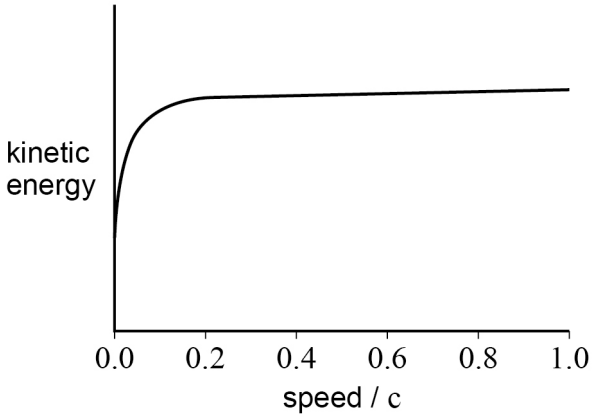
B



C



D



A ☐

B ☐

C ☐

D ☐

0 8 . 2 Calculate the speed of a particle when its kinetic energy is equal to its rest energy.

[3 marks]

speed = _____ $\mathrm{m\ s^{-1}}$

0 8 . 3 Discuss the change in the observed mass of a spring when it is stretched.

[2 marks]

_____

_____

_____

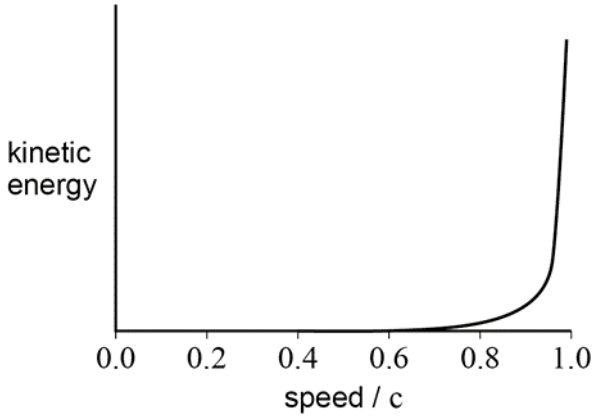
_____

_____

_____

6

END OF QUESTIONS

Question	Answers	Additional comments/Guidance	Mark	AO
08.1	C ✓  	Only answer	1	AO1

Question	Answers	Additional comments/Guidance	Mark	AO
08.2	KE = total energy – rest energy ✓ $m_0c^2 = \frac{m_0c^2}{\sqrt{1-\frac{v^2}{c^2}}} - m_0c^2$ ✓ To give $v = 0.87c$ OR 2.6×10^8 m s^{-1} ✓	MP2 requires the use of the idea that the KE is equal to the rest energy. (calculator values are 0.8660 and 2.59808 x 10^8)	3	3 x AO2

Question	Answers	Additional comments/Guidance	Mark	AO
08.3	mass is related to energy through $E = mc^2$ ✓ When an object stores energy this appears as an increase in observed mass. OR A spring gains (elastic potential) energy so observed mass must also increase. ✓	Treat any idea that 'the difference in observed mass is negligible' as neutral.	2	2 x AO3
Total			**6**	

0 9 Einstein developed his theory of special relativity from two postulates. One postulate states that physical laws have the same form in all inertial frames.

0 9 . 1 State the other postulate and explain how it is consistent with the equation:

$$c = \sqrt{\frac{1}{\mu_0 \varepsilon_0}}$$

[2 marks]

A proton leaves a particle accelerator at point **X** and moves at a constant speed towards a target at point **Y**.
The speed of the proton is $2.5 \times 10^8 \text{ m s}^{-1}$ in the frame of reference of the target.

The distance **XY** in the frame of reference of the proton is 38 m.

0 9 . 2 Calculate the distance **XY** in the frame of reference of the target.

[2 marks]

distance **XY** in the frame of reference of the target = _____ m

0 9 . 3 Show that the kinetic energy E_k of the proton is about 1.2×10^{-10} J.

[3 marks]

0 9 . 4 Sketch on **Figure 4** the variation of E_k with speed v for a proton.

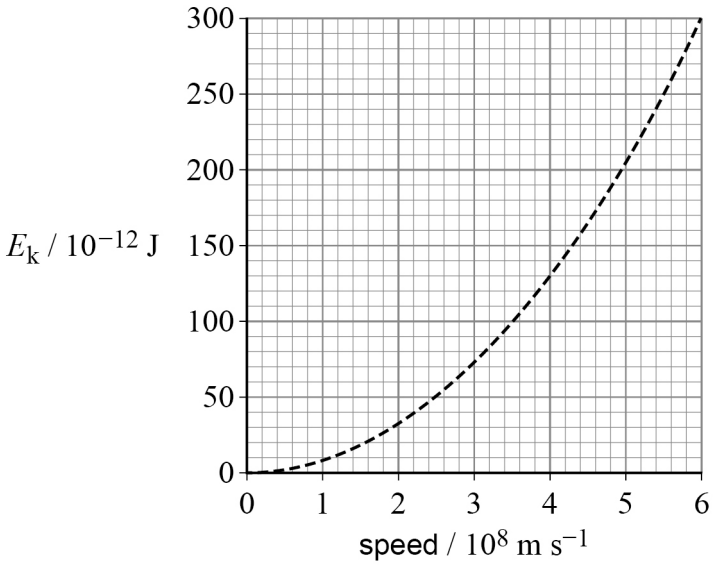
To help you, the dashed line represents

$$E_k = \frac{1}{2} m_0 v^2$$

where m_0 is equal to the mass of a proton at rest.

[3 marks]

Figure 4



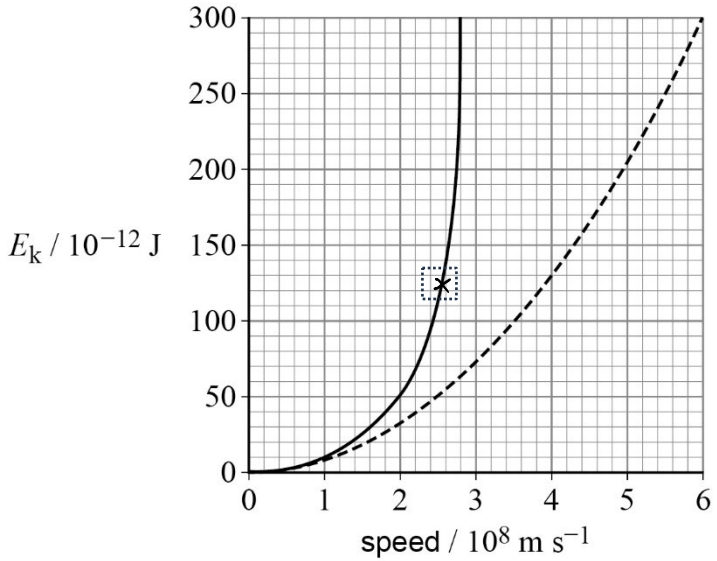
10

END OF QUESTIONS

Question	Answers	Additional comments/Guidance	Mark	AO
09.1	Either • Equation (for speed of light) only contains (universal) constants **OR** • Speed of light is invariant / constant / same in all reference frames / does not depend of speed of source or observer. ✓ Both bullet points above and **one** from • Constants don't depend on reference frame or speed of source / observer **OR** • (refers to the) speed of light as being in free space / vacuum ✓	Speed of light is constant in equation is not enough for MP1. Do NOT allow speed of light is invariant in all inertial reference frames for MP2 but condone for MP1. Ignore calculations of speed of light	2	1 × AO1 1 × AO3

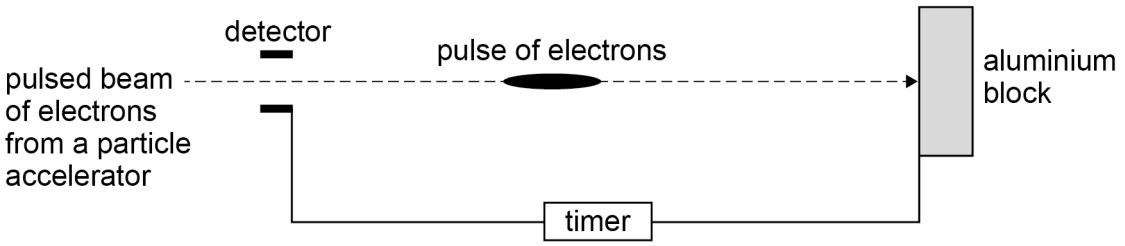
Question	Answers	Additional comments/Guidance	Mark	AO
09.2	Use by manipulation or substitution of $l = l_0\sqrt{1-\frac{v^2}{c^2}}$ ✓ to give 69 m ✓	Condone substitution and working leading to 21 m e.g. $38\sqrt{1-\frac{2.5^2}{3^2}} = 21$ for 1 mark only. (mixes up l_0 and l) $l_0 = \frac{l}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{38}{\sqrt{1-\frac{2.5^2(\times 10^8)^2}{3.0^2(\times 10^8)^2}}}$ Allow use of $v = \frac{s}{t}$ and $t = \frac{t_0}{\sqrt{1-\frac{v^2}{c^2}}}$ for either route. 93 m comes from $\frac{38}{\sqrt{1-\frac{2.5}{3.0}}}$ and gains 1 mark.	2	2 × AO2

Question	Answers	Additional comments/Guidance	Mark	AO
09.3	Evidence of idea that kinetic energy = total energy – rest energy ✓ $E_k = \frac{m_0 c^2}{\sqrt{1-\frac{v^2}{c^2}}} - m_0 c^2$ with substitutions correct ✓ 1.21 or 1.22×10^{-10} (J) ✓	If no other mark awarded, give one mark for calculation of total energy (2.72×10^{-10} J) or rest energy (1.5×10^{-10} J) Use of $m = \frac{m_0}{\sqrt{1-\frac{v^2}{c^2}}}$ with $E_k = \frac{1}{2}mv^2$ is 0 marks In MP2 allow use of γ from earlier 04.2 but value must be seen here. Allow rest energy = $931.5 \times 10^6 \times 1.60 \times 10^{-19}$ as part of calculation. At least 3 sf Allow 1.23×10^{-10} (J) A substitution missing the squares and showing 2.2×10^{-10} J is eligible for MP2.	3	3 × AO2

Question	Answers	Additional comments/Guidance	Mark	AO
09.4	Follows dashed line up to $v = 1$; condone divergence starting anywhere from $v = 0.3$ to $v = 1.1$ ✓ Increasing gradient passing within one grid square of $(2.5, 122)$ ✓ Increasing gradient and does not go beyond $v = 3$ ✓  	For MP3, if line reaches $v = 3$ must be asymptoti'c MP3 should not be awarded if continuing the line would clearly cross $v = 3$	3	3 × AO3.1a
Total			**10**	

1 0 **Figure 3** shows a modern version of Bertozzi's experiment to measure the kinetic energy of high-speed electrons. A timer is used to measure the time taken for a pulse of electrons to travel from the detector to the aluminium block.

Figure 3



1 0 . 1 A potential difference (pd) of $1.30\ \text{MV}$ is used to accelerate the electrons.

Show that each electron gains approximately $2 \times 10^{-13}\ \text{J}$ of kinetic energy.

[1 mark]

1 0 . 2 These electrons cause the temperature of the aluminium block to increase by $68.0\ \text{K}$. The number of electrons that cause this increase in temperature is 4.50×10^{17}

Deduce whether this increase in temperature is consistent with an accelerating pd of $1.30\ \text{MV}$.

specific heat capacity of aluminium $= 903\ \text{J kg}^{-1}\ \text{K}^{-1}$
mass of aluminium block $= 1.50\ \text{kg}$

[2 marks]

1 0 . 3 The speed of the electrons between the detector and the block is 2.88×10^8 m s^{-1}.

Student **A** suggests that the non-relativistic equation for kinetic energy could be used.
Student **B** suggests that the relativistic equation for kinetic energy is required in this situation.

Evaluate the suggestions of student **A** and student **B**.
Support your answer with calculations.

[4 marks]

Question 4 continues on the next page

1 0 . 4 The timer in **Figure 3** records a time of 29.8 ns.

What is the proper time interval for an electron travelling from the detector to the aluminium block?

Tick (✓) **one** box.

[1 mark]

< 29.8 ns ☐

29.8 ns ☐

> 29.8 ns ☐

1 0 . 5 The electrons in **Figure 3** were accelerated from rest in 13 stages.

In each stage the electrons were accelerated by a pd of 100 kV.

As a result, an electron increases its speed and kinetic energy during each stage.

Compare, for an electron,
- its increase in speed for the first stage with that for the last stage
- its increase in kinetic energy for the first stage with that for the last stage.

Justify your answer.

No further calculations are required.

[4 marks]

12

END OF QUESTIONS

Question	Answers	Additional comments/Guidance	Mark	AO
10.1	Either conversion of $1\ \text{MeV}$ to J or $W = QV$ $1.60 \times 10^{-19} \times 1.30 \times 10^{6} = 2.08 \times 10^{-13}$ ✓ (J)	At least 2 sf required.	1	1 AO1

Question	Answers	Additional comments/Guidance	Mark	AO
10.2	$Q = mc\Delta\theta = 1.5 \times 903 \times 68.0\ (= 92\ 106\ \text{J})$ **OR** E_{K} of one electron = $\frac{92\ 106}{4.50 \times 10^{17}}$ ✓$\left(= 2.05 \times 10^{-13}\ \text{J}\right)$ Both calculations and correct conclusion, eg Yes, this is consistent with an accelerating voltage of 1.30 MV. ✓	Alternative route Total E_{K} for all electrons = $2.08 \times 10^{-13} \times 4.50 \times 10^{17} = (93\ 600\ \text{J})$ **OR** $\Delta\theta = \frac{Q}{mc} = \frac{93600}{1.5 \times 903}$ ✓$(= 69.1\ \text{K})$ which is consistent with the temperature rise observed. ✓ Can also compare total E_{K} with $mc\Delta\theta$ for MP2. Use of 2.0×10^{13} gives total E_{K} of $90\ 000\ \text{J}$ and $\Delta\theta$ of $66\ \text{K}$ which is consistent. Allow comparison of in eV or accelerating pd (1.28×10^{6}) with 1.3×10^{6} V or MeV with MV.	2	2 AO3

Question	Answers	Additional comments/Guidance	Mark	AO
10.3	Correct calculation of non-relativistic E_K ✓a Statement or attempted use of $E_K = mc^2 - m_0c^2$ ✓b Correct calculation of relativistic E_K ✓c Both calculations and comparison of with 2.1 × 10^{-13} or 2.0 × 10^{-13} J to conclusion consistent with idea that student B is correct ✓d **Alternative** Calculation of speed using $v = \sqrt{\frac{2E_k}{m}}$ ✓a Statement or attempted use of $E_K = mc^2 - m_0c^2$ ✓b Calculation of speed from relativistic equation ✓c Both calculations and comparison of results with 2.88×10^8 or 3×10^8 ✓d **Alternative** for Max 2 Correct calculation of non-relativistic E_K ✓a Calculation of relativistic mass, total energy or $\sqrt{1 - v^2/c^2}$ or $\frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$ **AND** comment that **relativistic effects are significant (owtte)** so B is correct. ✓bcd	$E_K = \frac{1}{2}mv^2 = 3.78 \times 10^{-14}$ J $E = \frac{m_0c^2}{\sqrt{1-\frac{v^2}{c^2}}} - m_0c^2 = 2.11 \times 10^{-13}$ J For ✓d allow a comparison of $\Delta\theta$ from $m_{Al}c\Delta\theta = N(mc^2 - m_0c^2)$ with 68° Allow ecf for ✓d for minor calculation error, rounding error or transcription errors but there must be a relativistic KE and non-relativistic calculation to award ✓d. $v = 6.8 \times 10^8$ m s^{-1} if using 2.08×10^{-13} $v = 2.88 \times 10^8$ m s^{-1} if using 2.08×10^{-13} Allow calculations based on the total number of electrons and comparison with **04.2**. If no other marks awarded max 1 for student B is correct because speed is greater than 3.0×10^7 m s^{-1} or v is 96% of c (which is greater than 10%).	4	4 AO3

Question	Answers	Additional comments/Guidance	Mark	AO
10.4	< 29.8 ns ✓		1	1 AO2

Question	Answers	Additional comments/Guidance	Mark	AO
10.5	Max 4 • **Gain/change in** E_K is the same ✓a • due to the same loss of potential energy **OR** gain in $E_K = e(\Delta)V$ and same potential difference ✓b • **Increase/change** in speed is greater in stage 1 ✓c • Idea that mass increases with speed ✓d • Idea that energy is used to produce a large increase of mass and a small increase in speed in stage 13 (with a small increase in mass and a large increase in speed in stage 1) ✓e1 **OR** Idea that electron speed cannot increase much when close to the speed of light since electrons cannot travel faster than the speed of light ✓e2	Only allow use of $\frac{1}{2}mv^2$ or $E_K \propto v^2$ if it is clear that this refers only to stage 1 for ✓b or ✓e. ✓d Allow a correct sketch of relativistic mass and speed graph if c is labelled on speed axis. ✓d Condone with reference to $E_K = \frac{1}{2}mv^2$ ✓e must refer to relativity.	4	4 AO3
Total			**12**	

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

1 1 . 1 Explain what is meant by this postulate.

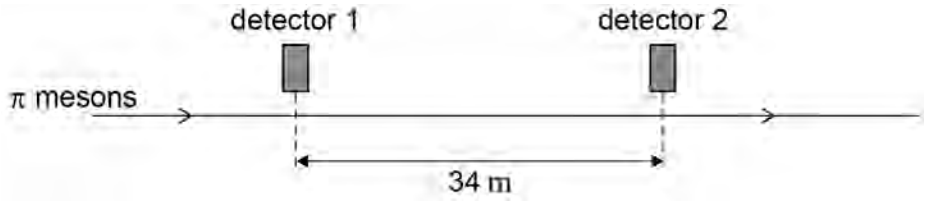
[1 mark]

1 1 . 2 State the other postulate.

[1 mark]

1 1 . 3 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 $0.95c$ past the two detectors, as shown in **Figure 5**.

Figure 5



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

[1 mark]

time = _____

1 1 . 4 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 marks]

END OF QUESTIONS

11.1	speed of light in free space independent of motion of source and/or the observer✓ and of motion of observer		1	
11.2	laws of physics have the same form in all inertial frames laws of physics unchanged from one inertial frame to another ✓		1	
11.3	time taken(= $\frac{\text{distance}}{\text{speed}}$ = $\frac{34\text{ m}}{0.95 \times 3.0 \times 10^8\text{ m s}^{-1}}$)=1.2×10^{-7} s✓		1	
11.4	$t = \frac{18\text{ ns}}{(1 - 0.95^2 c^2 / c^2)^{1/2}}$ ✓ time taken for π meson to pass from one detector to the other = 58 ns ✓ 2 half-lives (approximately) in the detectors' frame of reference . ✓ 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✓ 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)	Allow substitution for this mark	1 1 1 1 1	