1)

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|---|---|---|
| (a) | c is the same, regardless of the speed of the light source or the observer ✓ | 1 |
| (b) | distance between detectors in rest frame of particles<br>(= 25 × (1- 0.98$^2$)$^{1/2}$) = 5.0 m ✓<br>time taken in rest frame of particles $\left(= \frac{distance}{speed} = \frac{5.0}{0.98c}\right)$ = 1.7 × 10$^{-8}$ s ✓<br>time taken to decrease by ¼ = 2 half lives ✓<br>half life (= 1.7 × 10$^{-8}$/2) = 8.5 × 10$^{-9}$ s ✓<br>[**alternatively**<br>time taken in rest frame of detectors $\left(= \frac{distance}{speed} = \frac{25.0}{0.98c}\right)$ = 8.5 × 10$^{-8}$ s<br>time taken in rest frame of particles (= 8.5 × 10$^{-8}$ × (1-0.98$^2$)$^{1/2}$) =1.7 × 10$^{-8}$ s)] | 4 |
| | **Total** | 5 |

2)

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|---|---|---|---|
| a | i | $d_0$ =(speed × time = 1.8 × 10$^8$ × 95 × 10$^{-9}$) = 17(.1) m ✓ | 1 |
| a | ii | $d$ (= $d_0$ (1 – $v^2/c^2$)$^{½}$)<br>= 17.1 × (1 – (1.8 × 10$^8$/3.0 × 10$^8$)$^2$))$^{½}$ ✓<br>= 14 m ✓ (or 13.7 m or 13.68 m)<br>**or** $t = t_0$ (1 – $v^2/c^2$)$^{-½}$<br>95 = $t_0$ × (1 – (1.8 × 10$^8$/3.0 × 10$^8$)$^2$)$^{-½}$ gives $t_0$ = 76 ns ✓<br>$d = vt_0$ = 1.8 × 10$^8$ × 76 × 10$^{-9}$ = 14 m ✓ (or 13.7 m or 13.68 m) | 2 |
| b | | $m$ (= $m_0$ (1 – $v^2/c^2$)$^{-½}$)<br>= 1.67(3) × 10$^{-27}$ × (1 – (1.8 × 10$^8$/3.0 × 10$^8$)$^2$)$^{-½}$) ✓<br>= 2.09 × 10$^{-27}$ kg ✓<br>kinetic energy = ($m$ – $m_0$) $c^2$<br>**or** correct calculation of $E = mc^2$ (= 1.88 × 10$^{-10}$ J)<br>**or** correct calculation of $E_0 = m_0c^2$ (= 1.50 × 10$^{-10}$ J)✓<br>$\frac{\text{kinetic energy}}{\text{rest energy}} = \frac{(m - m_0)c^2}{m_0c^2} = \frac{(2.09 - 1.67) \times 10^{-27}}{1.67 \times 10^{-27}}$ ✓<br>= 0.25 (allow 0.245 to 0.255 or ¼ or 1:4) ✓ | 5 |
| | | **Total** | 8 |

3)

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| a) | | (A frame of reference ) that has a constant velocity ✓ | 1 | accept no acceleration |

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| b) | (i) | Distance = 4.3 $c$ light years ( or 4.1 x $10^{16}$ m)<br><br>Speed (= $\frac{4.3\,c}{5.0}$ ) = 2.6 x $10^8$ m $s^{-1}$ ( or 0.86 $c$ ) | 1 | Correct answer only gets the mark<br><br>Accept 2.58 |

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| (b) | (ii) | $t = \left(\frac{t_o}{(1 - v^2/c^2)^{1/2}}\right)$ where $t$ = 5.0 years (or 1.58 x $10^8$ s)<br>and $v$ = 0.86 $c$ (or 2.58 x $10^8$ m $s^{-1}$)<br><br>1st mark for correct substitution of either $t$ or $v$ into the above eqn ✓<br>$t_o$ = 5.0 x ( 1 - $(0.86c)^2/c^2)^{1/2}$ ✓ = 2.6 years ✓<br><br>**Alt scheme**<br>$l = l_o(1 - v^2/c^2)^{1/2}$ where $t$ = 5.0 years (or 1.58 x $10^8$ s) and $v$ = 0.86 $c$(or 2.58 x $10^8$ m $s^{-1}$)<br><br>1st mark for correct substitution of either $t$ or $v$ into the above eqn ✓<br>( $l_o$ = 4.3 x 365 x 24 x 3600 x 3.0 x $10^8$ = 4.07 x $10^{16}$ m)<br><br>$l$ = 4.07 x $10^{16}$ (1 - $(0.86c)^2/c^2)^{1/2}$ or 2.08 x $10^{16}$ m✓<br><br>$t_o = \frac{l}{v}$ ( = $\frac{2.08 \times 10^{16}\text{ m}}{2.6 \times 10^8\text{ m/s}}$ = 8.05 x $10^7$s) = 2.6 years ✓ | 3 | CF from bi to bii provided answer to bi < $c$<br><br>Accept $t$ or $v$ in alternative units<br><br>Accept 1.58 (or 1.6) x $10^8$ s in place of 5.0 yr in 3rd mark point<br><br>Accept 2.5 to 2.6 to any number of sfs<br><br>Alternative for last 2 marks in Alt scheme<br>( $l_o$ = 4.3 l yr)<br><br>$l$ = 4.3 (1 - $(0.86c)^2/c^2)^{1/2}$ = 2.2 l yr✓<br><br>$t_o = \frac{l}{v}$ (= $\frac{2.2}{0.86}$ ) = 2.6 years ✓ |

4)

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|---|---|---|---|
| (a)(i) | Distance travelled in muons' frame of reference<br>= 10700(1-$0.996^2)^{1/2}$ =956 m✓<br>Time taken in muons' frame of reference = 3.2 μs✓<br>This is 2 half-lives so number reaching Earth = 250✓<br>**OR**<br>Time in Earth frame of reference<br>= 10700/(0.996 x 3 x $10^8$) = 3.581 x $10^{-5}$ s✓<br>Time taken in muons' frame of reference = 3.2 μs✓<br>This is 2 half-lives so number reaching Earth = 250✓<br>**OR**<br>Half-life in Earth frame of reference<br>=1.6 X $10^{-6}$/(1-$0.996^2)^{1/2}$ = 17.9x $10^{-6}$ s✓<br>Time taken = 35.8 x $10^{-6}$ s✓<br>This is 2 half lives so number reaching Earth = 250✓<br>**OR**<br>Distance travelled in muons' frame of reference<br>= 10700(1-$0.996^2)^{1/2}$ =956 m✓<br>Distance the muon travels in one half-life in muons reference frame<br>= 0.996 x 3 x $10^8$ x 1.6 x $10^{-6}$ = 478 m✓<br>Therefore 2 half-lives elapse to travel 956 m so number = 250✓<br>**OR**<br>decay constant in muon frame of reference<br>or decay constant in the Earth frame of reference✓<br><br>Uses the corresponding elapsed time and decay constant in<br>$N = N_o e^{-\lambda t}$✓<br>Arrives at 250✓ | All steps in the working must be seen<br>Award marks according to which route they appear to be taking.<br><br>The number left must be deduced from the correct time that has elapsed in the frame of reference they are using. | 3 |

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| (a)(ii) | <table><tr><td></td><td>✓ if correct</td></tr><tr><td>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</td><td>✓</td></tr><tr><td>For an observer in a laboratory on Earth time passes more slowly than for a muon in its frame of reference</td><td></td></tr><tr><td>For an observer in a laboratory on Earth, the probability of a muon decaying each second in lower than it is for a muon in its frame of reference</td><td></td></tr></table> | | 1 |
| (b)(i) | Total energy = 9.11 x $10^{-31}$ x (3 x $10^{8})^{2}/(1-0.98^{2})^{1/2}$✓<br>4.12 x $10^{-13}$ J seen to 2 or more sf✓ | Show that so working must be seen | 2 |
| (b)(ii) | Change = 7.5 x $10^{-14}$ J<br>$V$ = 469 (470) kV allow ecf using their answer to (b)(i) ✓ | ecf is their ((b)(i) –3.37)x$10^{-13}$)/1.6 x $10^{-19}$<br>Using 4 x $10^{-13}$ gives 394 (390)kV<br>Using 3.9 x $10^{-13}$ gives 331(330) kV<br>Do not allow 1 sf answer | 1 |

5)

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|---|---|---|---|---|
| (a) | | (Using $m = \frac{m_o}{\sqrt{1-\frac{v^2}{c^2}}}$ gives )<br>$2 = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$ or $\sqrt{1-\frac{v^2}{c^2}} = 0.5$ ✓<br>(Rearranging gives)<br>$v$ (= $\sqrt{1-0.5^2}$ $c$) = 0.866 $c$ or 2.6 × $10^8$ m $s^{-1}$ ✓ | 2 | Accept either answer. |
| (b) | | curve starts at $v$=0 , $m = m_o$ and rises smoothly ✓<br>curve passes through $2m_o$ at $v$ = 0.87 $c$ (± 0.03$c$ or in 2nd half of x-scale div containing 0.87c) ✓<br>curve is asymptotic at $v = c$ ( and does not cross or touch $v$ =$c$ or curve back ) ✓ | 3 | 2nd mark ; ecf from 4a if plotted correctly<br>3rd mark ; There must be visible white space between the curve and the v = c line; also, the curve must reach 7$m_o$ at least. |
| (c) | | Energy = $mc^2$ so (as $v$ -> $c$ ) energy of particle increases as mass increases ✓<br>mass -> infinity as $v$ -> $c$ so energy -> infinity which is (physically) impossible ✓<br>[OR for one mark only<br>force = $ma$ so force increases as mass increases<br>Mass -> infinity as v->c so force -> infinity which is (physically ) impossible✓] | 2 | Alternative scheme for 1 mark only ; mass infinite at $v = c$ which is (physically) impossible ✓ |

6)

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|---|---|---|---|
| a | | bright (or dark) fringe is seen where the two beams are in phase (or out of phase by 180°) ✓<br>changing the distance to either mirror changes the path (or phase) difference (between the two beams) so fringes shift ✓ | 2 |

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| b | i | speed of light was thought to depend on the speed of the light source (or the speed of the observer) ✓ (or on the motion of the Earth (through the aether))<br>distance travelled by each beam unchanged (by rotation)✓<br>time difference between the two beams would change on rotation ✓<br>phase difference would therefore change (so fringes would shift) ✓ | max 3 |

| | | | |
|---|---|---|---|
| b | ii | speed of light is independent of the speed (or motion) of the light source (or the observer) ✓<br>(or 'aether' hypothesis incorrect (owtte)) or absolute motion does not exist) | 1 |