M1. (i) $v\left(= \frac{45}{152 \times 10^{-9}}\right) = 2.96 \times 10^{8}\ \text{m s}^{-1}$ **(1)**

2

(ii) t = 152 ns **(1)**

$$t_0 \left[= 152\left(1 - \frac{v^2}{c^2}\right)^{1/2} \right] = 152\left(1 - \left(\frac{2.96}{3.00}\right)^2\right)^{1/2} \quad \textbf{(1)}$$

= 25 ns **(1)**

2

QWC 2

[4]

M2. (a) (i) two beams (or rays) reach the observer **(1)**
interference takes place between the two beams **(1)**
bright fringe formed if/where (optical) path difference = whole number of wavelengths
(or two beams in phase)
[or dark fringe formed if/where (optical) path difference = whole number + 0.5 wavelengths]
(or two beams out of phase by 180 °C/ π/2 /½ cycle) **(1)**

(ii) rotation by 90° realigns beams relative to direction of Earth's motion **(1)**
no shift means no change in optical path difference between the two beams **(1)**
(∴) time taken by light to travel to each mirror unchanged by rotation **(1)**
distance to mirrors is unchanged by rotation **(1)**
(∴) no shift means that the speed of light is unaffected [or disproves other theory] **(1)**

max 5

(b) the speed of light does not depend on the motion of the light source **(1)** or that of the observer **(1)**

2

[7]

M3. (a) Newton's laws obeyed in an inertial frame
[or inertial frames move at constant velocity relative to each other] **(1)**
suitable example (e.g. object moving at constant velocity) **(1)**

2

(b) (i) (use of $t = t_0\left(1-\frac{v^2}{c^2}\right)^{-1/2}$ gives) t_0 = 18 (ns) **(1)**

$t = 18 \times 10^{-9}\left(1-\frac{(0.995c)^2}{c^2}\right)^{-1/2}$ **(1)**

$= 1.8 \times 10^{-7}$ s **(1)**

(ii) time taken $\left(=\frac{\text{distance}}{\text{speed}}\right) = \left(\frac{108}{0.995 \times 3.0 \times 10^8}\right) = 3.6 \times 10^{-7}$ s **(1)**

time taken = 2 half-lives, which is time to decrease to 25% intensity **(1)**

[alternative scheme: (use of $l = l_0\left(1-\frac{v^2}{c^2}\right)^{1/2}$ gives) l_0 = 108 (m)

$l = 108\left(1-\frac{(0.995c)^2}{c_2}\right)^{1/2}$ = 10.8 m **(1)**

time taken $\left(=\frac{10.8}{0.995c}\right) = 3.6 \times 10^{-8}$ s

= 2 half-lives, which is time to decrease to 25% intensity **(1)**]

5

[7]

M4. (i) E_k (= eV) (= $1.6 \times 10^{-19} \times 1.1 \times 10^9$)

$= 1.8 \times 10^{-10}$ (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) $2.2m_0 = \left(1-\frac{v^2}{c^2}\right)^{-1/2}$ **(1)**

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

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

[7]

M5. (a) (i) $t_0 = 800$ (s) **(1)**

(use of $t = t_0\left(1-\frac{v^2}{c^2}\right)^{-\frac{1}{2}}$ gives) $t = 800(1 - 0.994^2)^{-1/2}$**(1)**

$= 7300$ s **(1)**

(ii) distance (= 0.994*ct* = 0.994 × 3 × 10^8 × 7300)

$= 2.2 \times 10^{12}$m **(1)** (2.18×10^{12}m)

(allow C.E. for value of *t* from (i))

4

(b) space twin's travel time = proper time (or t_0) **(1)**

time on Earth, $t = t_0\left(1-\frac{v^2}{c^2}\right)^{-\frac{1}{2}}$ **(1)**

$t > t_0$

[or time for traveller slows down compared with Earth twin] **(1)**

space twin ages less than Earth twin **(1)**

travelling in non-inertial frame of reference **(1)**

max 3

[7]

M6. (a) $10m_0 = m_0\left(1-\frac{v_2}{c^2}\right)^{-\frac{1}{2}}$ **(1)**

gives $\frac{v^2}{c^2}$ = 1 – 0.01 = 0.99 **(1)**

v (= 0.995c) = 2.98(5) × 10^8 m s^{-1} **(1)**

3

(b) $m = m_0\left(1 - \frac{v_2}{c^2}\right)^{-\frac{1}{2}}$ **(1)**

$m \rightarrow$ infinity as $v \rightarrow c$ **(1)**

[or m increases as v increases]

$E_k(= mc^2 - m_0c^2) \rightarrow$ infinity as $v \rightarrow c$ **(1)**

$v = c$ would require infinite E_k (or mass) which is (physically)

impossible **(1)**

Max 3

[6]

M7. (i) time taken $\left(\frac{distance}{speed} = \frac{34}{0.95 \times 3.0 \times 10^8}\right) = 1.1(9) \times 10^7$ s **(1)**

(ii) use of $t = \frac{t_0}{(1 - v^2/c^2)^{1/2}}$ where t_0 = 18 ns

and t is the half-life in the detectors' frame of reference **(1)**

$\therefore\ t = \frac{18 \times 10^{-9}}{(1 - 0.95^2)^{1/2}} = 57(.6) \times 10^{-9}$ s (1)

time taken for п meson to pass from one detector to the other
= 2 half-lives (approx) (in the detectors' frame of reference) **(1)**
2 half-lives correspond to a reduction to 25%,
so 75% of the п mesons passing the first detector
do not reach the second detector **(1)**

alternatives for first 3 marks in (ii)

1. use of $t = \frac{t_0}{\sqrt{(1 - v^2/c^2}}$, where t_0 = 18 ns

$= \frac{18}{(1 - 0.95^2)^{1/2}}$ = 57.6(ns)

journey time in detector frame (= *2t) = 2* × 57.6ns (≈ 2 half-lives)

2. use of t = $\frac{t_0}{\sqrt{(1 - v^2/c^2}}$ where *t* = 119 ns

= journey time in detector frame

$t_0 = 119\sqrt{1 - 0.95^2}$ =37ns

journey time in rest frame = 2 × 18 ns (2 half-lives)

[5]

M8. (a) (i) speed of light in free space independent of motion of source **(1)**

and of motion of observer **(1)**

(ii) laws of physics have the same form in all inertial frames **(1)**

inertial frame is one in which Newton's 1st law of motion is obeyed **(1)**

laws of physics unchanged in coordinate transformation **(1)**

from one inertial frame to another **(1)**

max 4

(b) (i) m (= m_0 $(1 - v^2/c^2)^{-1/2}$) = 1.9 × 10^{-28} × $(1 - 0.995^2)^{-1/2}$(kg) **(1)**

= 1.9 × 10^{-27} kg **(1)**

(ii) E (= mc^2) = 1.9 × 10^{-27} × $(3.0 \times 10^8)^2$ **(1)**

= 1.7 × 10 ^{10} J **(1)**

(iii) E_K (= $E - m_0c^2$) = 1.7 × 10^{-10} (1.9 × 10^{-28} × $(3.0 \times 10^8)^2$) **(1)**

= 1.5 × 10^{-10}J **(1)**

6

[10]

M9. (a) c is the same, regardless of the speed of the light source or the observer **(1)**

1

(b) distance between detectors in rest frame of particles
(= 25 × $(1 - 0.98^2)^{1/2}$) = 5.0 m **(1)**

time taken in rest frame of particles $\left(= \frac{distance}{speed} = \frac{5.0}{0.98c}\right)$ = 1.7 × 10^{-8} s **(1)**

time taken to decrease by ¼ = 2 half lives **(1)**

half life (= 1.7 × 10^{-8}/2) = 8.5 × 10^{-9} s **(1)**

[**alternatively**

time taken in rest frame of detectors $\left(= \frac{distance}{speed} = \frac{25.0}{0.98c}\right)$ = 8.5 × 10^{-8} s
time taken in rest frame of particles
(= 8.5 × 10^{-8} × $(1 - 0.98^2)^{1/2}$) =1.7 × 10^{-8} s)]

4

[5]

M10. (a) (i) d_0 =(speed × time = 1.8 × 10^8 × 95 × 10^{-9}) = 17(.1) m ✓

1

(ii) d (= d_0 $(1 - v^2/c^2)^{½}$)

= 17.1 × $(1 - (1.8 \times 10^8/3.0 \times 10^8)^2))^{½}$ ✓

= 14 m ✓ (or 13.7 m or 13.68 m)

or

$t = t_0 (1 - v^2/c^2)^{-½}$

95 = t_0 × $(1 - (1.8 \times 10^8/3.0 \times 10^8)^2)^{-½}$ gives t_0 = 76 ns ✓

$d = vt_0$ = 1.8 × 10^8 × 76 × 10^{-9} = 14 m ✓ (or 13.7 m or 13.68 m)

2

(b) $m\ (= m_0\ (1 - v^2/c^2)^{-½})$

$= 1.67(3) \times 10^{-27} \times (1 - (1.8 \times 10^8/3.0 \times 10^8)^2)^{-½}$ ✓

$= 2.09 \times 10^{-27}$ kg ✓

kinetic energy $= (m - m_0)\ c^2$

or correct calculation of $E = mc^2$ ($= 1.88 \times 10^{-10}$ J)

or correct calculation of $E_0 = m_0c^2$ ($= 1.50 \times 10^{-10}$ J) ✓

$$\frac{\text{kinetic energy}}{\text{rest energy}} = \frac{(m - m_0)c^2}{m_0c^2} = \frac{(2.09 - 1.67) \times 10^{-27}}{1.67 \times 10^{-27}}$$ ✓

= 0.25 (allow 0.245 to 0.255 or ¼ or 1:4) ✓

5

[8]

M11. (a) bright (or dark) fringe is seen where the two beams are in phase (or out of phase by 180°) ✓

changing the distance to either mirror changes the path (or phase) difference (between the two beams) so fringes shift ✓

2

(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))

distance travelled by each beam unchanged (by rotation) ✓

time difference between the two beams would change on rotation ✓

phase difference would therefore change (so fringes would shift) ✓

3

(ii) speed of light is independent of the speed (or motion) of the light source (or the observer) ✓

(or 'aether' hypothesis incorrect (owtte)) or absolute motion does not exist)

1

[6]

M12. (a)

(Using $m = \dfrac{m_o}{\sqrt{1-\dfrac{v^2}{c^2}}}$ gives)

$$2 = \frac{1}{\sqrt{1-\dfrac{v^2}{c^2}}} \quad \text{or} \quad \sqrt{1-\frac{v^2}{c^2}} = 0.5 \ ✓$$

(Rearranging gives)

$v \ (= \sqrt{1-0.5^2}\ c) = 0.866\,c$ or 2.6×10^8 m s^{-1} ✓

Accept either answer.

2

(b) curve starts at v=0, $m = m_o$ and rises smoothly ✓

2nd mark; ecf from a if plotted correctly

curve passes through $2m_o$ at v = 0.87 c (± 0.03*c* or in 2nd half of x-scale div containing 0.87c) ✓

3rd mark; There must be visible white space between the curve and the v = c line; also, the curve must reach $7m_o$ at least.

curve is asymptotic at *v* = *c* (and does not cross or touch *v* =*c* or curve back) ✓

3

(c) Energy = mc^2 so (as *v* -> *c*) energy of particle increases as mass increases ✓

Alternative scheme for 1 mark only; mass infinite at v = c which is (physically) impossible ✓

mass -> infinity as *v* -> *c* so energy -> infinity which is (physically) impossible ✓

[OR for one mark only

force = *ma* so force increases as mass increases

Mass -> infinity as v->c so force -> infinity which is (physically) impossible ✓]

2

[7]