1. (a) (i) beam splitter [or semi-silvered mirror] **(1)**

(ii) a compensator [or a glass block] **(1)**
allows for the thickness of the (semi-silvered) mirror
to obtain equal optical path lengths in the
two branches of the apparatus) **(1)** 3

(b) (i) concentric rings **(1)**
an interference pattern **(1)**
[*alt:* whole view shows one shade **(1)** because there is
a constant phase difference**(1)**]

(ii) fringes [or rings] shift **(1)**
05λ extra for l_1 gives one complete fringe shift
[or fraction of wavelength extra causes noticeable fringe shift
or noticeable change of intensity (if uniform)] **(1)** 4

(c) (i) rotate apparatus through 90° **(1)**
observe the fringes at the same time **(1)**
observed fringes did not change [or shift] **(1)**

(ii) speed of light in free space is invariant
[or does not depend on motion of source or observer
or no evidence for absolute motion] **(1)** max 3

[10]

2. (a) (i) $l = (\upsilon t = 1.00 \times 10^8 \times 15 \times 10^{-9}) = 1.50\text{m}$ **(1)**

(ii) $\left(l = l_0 \sqrt{1 - \frac{\upsilon^2}{c^2}} \right)$

$1.50 = l_0 \sqrt{1 - \frac{(1.00 \times 10^8)^2}{(3.00 \times 10^8)^2}}$ **(1)**

$l_0 \left(= \frac{1.50}{0.943} \right) = 1.59\text{ m}$ **(1)** 3

(b) (i) $m = \dfrac{m_0}{\sqrt{1-\dfrac{\upsilon^2}{c^2}}}$ **(1)** $\left[\text{or} \dfrac{m_0}{\sqrt{1-\dfrac{(1.00\times10^8)^2}{(3.00\times10^8)^2}}}\right]$

$$m\left(=\frac{m_0}{\sqrt{1-\dfrac{(1.00\times10^8)^2}{(3.00\times10^8)^2}}}\right) = 1.06m_0$$

[or = $1.06 \times 1.67 \times 10^{-27}$ or 1.77×10^{-27} kg] **(1)**

kinetic energy = $(m - m_0)c^2$ **(1)**

[or = $0.06m_0c^2$ or $0.06 \times 1.67 \times 10^{-27} \times (3 \times 10^8)^2$]

= 9.1×10^{-12} (J) **(1)**

(ii) total k.e. = $(10^7 \times 9.1 \times 10^{-12}) = 9.1 \times 10^{-5}$(J) **(1)**

k.e. per second $\left(=\dfrac{9.1\times10^{-5}}{15\times10^{-9}}\right)$ = 6080W max 5

[8]

3. (a) no change in the fringe pattern on rotation **(1)**

the speed of light is the same in the two directions **(1)**

the speed of light from a light source on Earth is

unaffected by the motion of the Earth **(1)**

[or the speed of light is invariant

or independent of the motion of the source or observer] **(1)**

the laws of dynamics cannot be applied to light **(1)**

no ether **(1)** max 3

(b) (i) time $\left(=\dfrac{\text{distance}}{\text{speed}}=\dfrac{16cT_{\text{oneyear}}}{0.8c}\right)$ = 20 yr **(1)**

(ii) L_0 = 16c [or 16 light years] **(1)**

$$L\left(=L_0\left(1-\frac{\upsilon^2}{c^2}\right)^{\frac{1}{2}}\right) = 16(1-0.8^2)^{\frac{1}{2}} \quad (=0.6 \times 16c) = 9.6c \text{ } \mathbf{(1)}$$

(iii) $\Delta t = 20$ years **(1)**

$\Delta t_0 = \Delta t \left(1 - \frac{\upsilon^2}{c^2}\right)^{\frac{1}{2}} = 20(1–0.8^2)^{\frac{1}{2}}$ **(1)**

$= 0.6 \times 20 = 12$yr $\therefore$ age $= 21 + 12 = 33$ yr **(1)** 6

[9]

4. (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) $m \left(= m_0 \left(1 - \frac{\upsilon^2}{c^2}\right)^{-\frac{1}{2}} \right) = 1.88 \times 10^{-28} (1 - (0.996)^2)^{-\frac{1}{2}}$ **(1)**

$= 2.10 \times 10–^{27}$ kg **(1)**

(ii) $t_0 = 2.2 \times 10^{-6}$ s **(1)**

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

$= 2.46 \times 10^{-5}$ (s) **(1)**

$s (= \upsilon t = 3.00 \times 10^8 \times 0.996 \times 2.46 \times 10^{-5}) = 7360$ m **(1)**

[*alternative (ii)*
$l\left(= \upsilon t = 0.996 \times 3.0 \times 10^8 \times 2.2 \times 10^6\right)$ = 657 (m) **(1)**

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

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

l_0 = 7360 m **(1)** 6

[10]

5. (a) as speed → c, mass → infinite **(1)**
gain of E_k causes large gain of mass when speed is close to c **(1)**
gain of E_k causes small gain of speed when speed is close to c **(1)**
$E_k = ½mv^2$ valid at speeds <<c **(1)** max 3
QWC

(b) (i) $E_k = eV = 1.6 \times 10^{-19} \times 2.1 \times 10^{10}$ **(1)** **(**= $3.3(6) \times 10^{-9}$J)

(ii) (use of $m = \frac{E_k}{c^2}$ gives) gain of mass = $\frac{3.36\times10^{-9}}{(3\times10^8)^2} = 3.7\times10^{-26}$(kg) **(1)**

$$= \frac{3.7\times10^{-26}}{1.67\times10^{-27}} m_0 = 22\ m_0 \quad \textbf{(1)}$$

mass of proton = 22 m_0 +m_0 **(1)** (=23 m_0)

(using $E_k = 3.4 \times 10^{-9}$ gives gain of mass = 3.8×10^{-26} (kg) ≡ 23 m_0
mass of proton = 24 m_0 4

(c) $23 = \left(1-\frac{v^2}{c^2}\right)^{-1/2}$ **(1)**

$\frac{v^2}{c_2} = \left(1-\frac{1}{23^2}\right) = 0.998$ **(1)**

$v = 0.999\ c = 2.99(7) \times 10^8$ m s^{-1} 3

[10]

6. (a) (i) (use of $v = \frac{d}{t}$ gives) $v = \frac{240}{0.84\times10^{-6}} = 2.8(6) \times 10^8$ 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)

$l = (240 \times 0.30) = 72(.5)$ 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]

7. (i) $v\left(=\frac{45}{152\times10^{-9}}\right) = 2.96 \times 10^8$ m s^{-1} **(1)** 2

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

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

$= 25$ ns **(1)** 2

QWC 2

[4]

8. (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/ $\pi/2$ /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
(∴) 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 2

[7]

9. (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 $\left(=\dfrac{\text{distance}}{\text{speed}}\right)=\left(\dfrac{108}{0.995\times 3.0\times 10^{8}}\right)= 3.6 \times 10^{-7}$ s **(1)**

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

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

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

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

= 2 half-lives, which is time to decrease to 25% intensity **(1)**] 5

[7]

10. (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) $\Delta m = \left(\dfrac{1.8\times 10^{-10}}{(3\times 10^{8})^2}\right) = 2.0 \times 10^{-27}$ (kg) **(1)**

$= \dfrac{2.0\times 10^{-27}}{1.67\times 10^{-27}} m_0 = 1.2 m_0$ **(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 $m = m_0\left(1-\dfrac{v^2}{c^2}\right)^{-1/2}$ gives) $2.2 m_0 = \left(1-\dfrac{v^2}{c^2}\right)^{-1/2}$ **(1)**

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

= 2.7×10^8 m s^{-1} **(1)** 7

[7]

11. (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 ($= 0.994ct = 0.994 \times 3 \times 10^8 \times 7300$)

$= 2.2 \times 10^{12}$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]

12. (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 ($= 0.995c$) $= 2.98(5) \times 10^8$ 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]

13. (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 $t = \dfrac{t_0}{(1 - v^2/c^2)^{1/2}}$ where t_0 = 18 ns

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

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

time taken for π 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 π mesons passing the first detector
do not reach the second detector **(1)**

alternatives for first 3 marks in (ii)

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

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

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

2. use of t = $\dfrac{t_0}{\sqrt{(1 - v^2/c^2}}$ 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]

14. (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) $m\ (= m_0\ (1 - v^2/c^2)^{-1/2})\ = 1.9 \times 10^{-28} \times (1 - 0.995^2)^{-1/2}$(kg) **(1)**

$= 1.9 \times 10^{-27}$ kg **(1)**

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

$= 1.7 \times 10^{\,10}$ J **(1)**

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

$= 1.5 \times 10^{-10}$J **(1)** 6

[10]