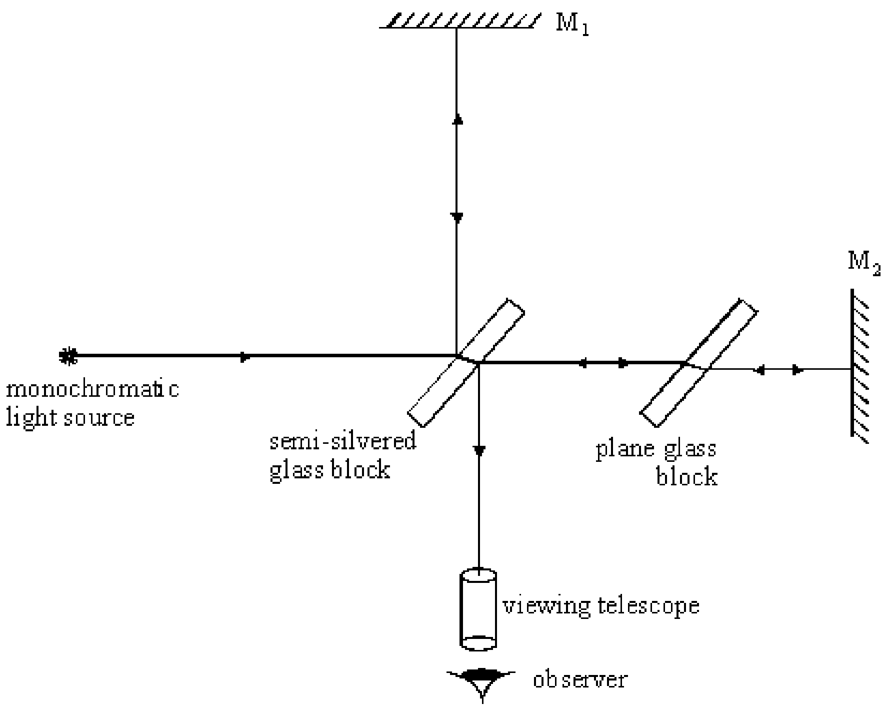
Q1. The Michelson-Morley experiment represented in the diagram was designed to find out if the speed of light depended on its direction relative to the Earth's motion through space. Interference fringes were seen by the observer.



(a) (i) Explain why interference fringes were seen.

....

....

....

....

....

(ii) The interference fringe pattern did not shift when the apparatus was rotated by 90°. Explain the significance of this null observation.

....

....

....

....

....

(5)

(b) Einstein postulated that the speed of light in free space is invariant. Explain what is meant by this postulate.

....

....

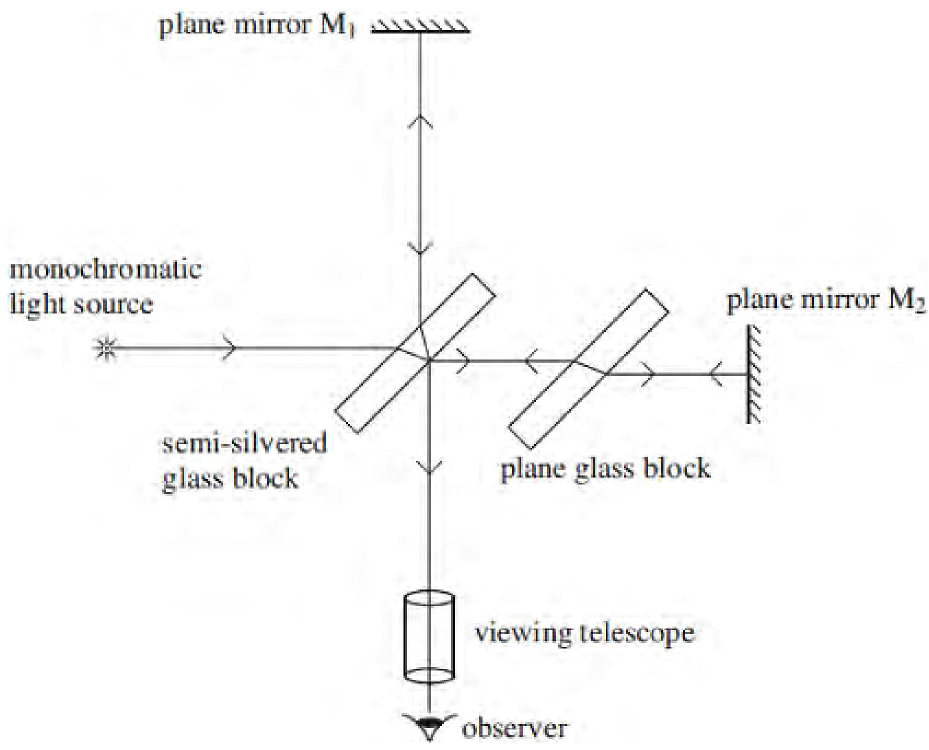
....

....

....

(2)
(Total 7 marks)

Q2. The figure below represents the Michelson-Morley interferometer. Interference fringes are seen by an observer looking through the viewing telescope.



(a) Explain why the interference fringes shift their position if the distance from either of the two mirrors to the semi-silvered block is changed.

....

....

....

....

....

....

(b) Michelson and Morley predicted that the interference fringes would shift when the apparatus was rotated through 90°. When they tested their prediction, no such fringe shift was observed.

(i) Why was it predicted that a shift of the fringes would be observed?

....

....

....

....

....

....

....

....

....

....

....

(3)

(ii) What conclusion was drawn from the observation that the fringes did not shift?

....

....

....

....

(1)
(Total 6 marks)

Q3. (a) One of the two postulates of Einstein's theory of special relativity is that *physical laws have the same form in all inertial frames of reference*.

Explain, with the aid of a suitable example, what is meant by an inertial frame of reference.

....

....

....

....

....

(2)

(b) A certain type of sub-atomic particle has a half-life of 18 ns when at rest. A beam of these particles travelling at a speed of 0.995*c* is produced in an accelerator.

(i) Calculate the half-life of these particles in the laboratory frame of reference.

....

....

....

....

....

(ii) Calculate the time taken by these particles to travel a distance of 108 m in the laboratory at a speed of 0.995*c* and hence show that the intensity of the beam is reduced to 25% of its original value over this distance.

....

....

....

....

....

....

....

....

(5)
(Total 7 marks)

Q4. (a) One of the two postulates of Einstein's theory of special relativity is that the speed of light in free space, *c*, is invariant.

Explain what is meant by this statement.

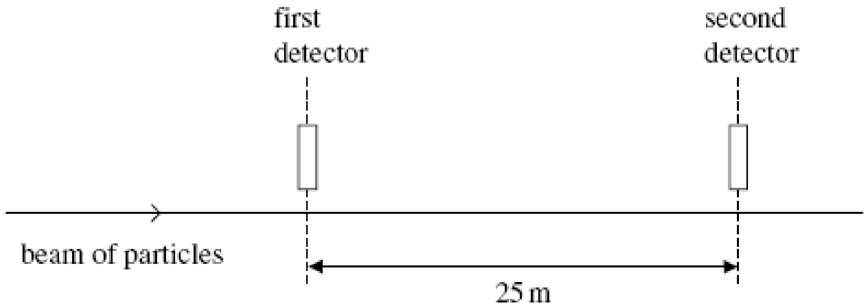
....

....

....

(1)

(b) A beam of identical particles moving at a speed of 0.98*c* is directed along a straight line between two detectors 25 m apart.



The particles are unstable and the intensity of the beam at the second detector is a quarter of the intensity at the first detector.

Calculate the half-life of the particles in their rest frame.

answer = ... s

(4)
(Total 5 marks)

Q5. (a) One of the two postulates of Einstein's theory of special relativity is that the speed of light in free space is invariant.

(i) Explain what is meant by this postulate.

....

....

....

....

(ii) State and explain the other postulate.

....

....

....

....

....

(4)

(b) A stationary muon has a rest mass of 1.9×10^{-28} kg.

For a muon travelling at a speed of 0.995 *c*, where *c* is the speed of light in a vacuum, calculate

(i) its mass,

....

....

....

....

(ii) it total energy, in J

....

....

....

....

(iii) its kinetic energy, in J.

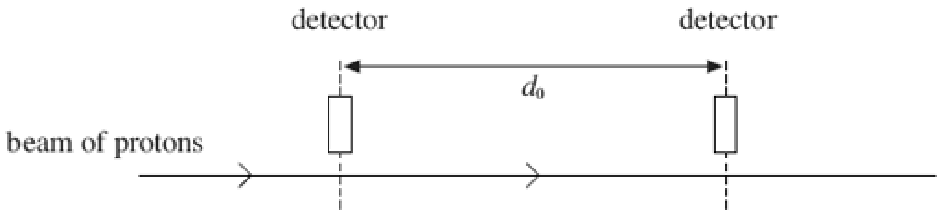
....

....

....

(6)
(Total 10 marks)

Q6. In an experiment, a beam of protons moving along a straight line at a constant speed of $1.8 \times 10^8 \text{ms}^{-1}$ took 95 ns to travel between two detectors at a fixed distance d_0 apart, as shown in the figure below.



(a) (i) Calculate the distance d_0 between the two detectors in the frame of reference of the detectors.

answer = ... m

(1)

(ii) Calculate the distance between the two detectors in the frame of reference of the protons.

answer = ... m

(2)

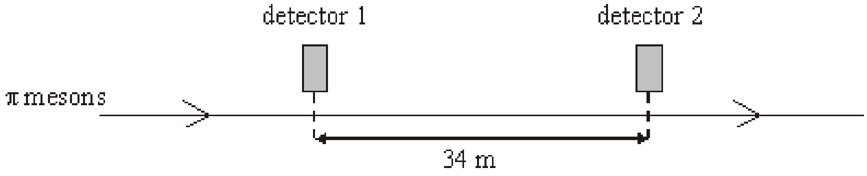
(b) A proton is moving at a speed of $1.8 \times 10^8 \text{ms}^{-1}$

Calculate the ratio $\dfrac{\text{kinetic energy of the proton}}{\text{rest energy of the proton}}$

answer = ...

(5)
(Total 8 marks)

Q7. π mesons, travelling in a straight line at a speed of 0.95 *c*, pass two detectors 34 m apart, as shown in the figure below.



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

....

....

....

(ii) π mesons are unstable and decay with a half-life of 18 ns when at rest. Show that approximately 75% of the π mesons passing the first detector decay before they reach the second detector.

....

....

....

....

....

....

(Total 5 marks)

Q8. (a) Calculate the speed at which a matter particle has a mass equal to 10 times its rest mass.

....

....

....

....

....

....

(3)

(b) Explain why a matter particle can not travel as fast as a photon in free space even though its kinetic energy can be increased without limit.

....

....

....

....

....

....

....

(3)
(Total 6 marks)

Q9. (a) In a science fiction film, a space rocket travels away from the Earth at a speed of 0.994 c, where c is the speed of light in free space. A radio message of duration 800 s is transmitted by the space rocket.

(i) Calculate the duration of the message when it is received at the Earth.

....

....

....

....

(ii) Calculate the distance moved by the rocket in the Earth's frame of reference in the time taken to send the message.

....

....

....

(4)

(b) A student claims that a twin who travels at a speed close to the speed of light from Earth to a distant star and back would, on return to Earth, be a different age to the twin who stayed on Earth. Discuss whether or not this claim is correct.

....

....

....

....

....

....

....

....

....

....

(3)
(Total 7 marks)

Q10. (i) Calculate the kinetic energy, in J, of a proton accelerated in a straight line from rest through a potential difference of 1.1×10^9 V.

....

....

(ii) Show that the mass of a proton at this energy is 2.2 m_0, where m_0 is the proton rest mass.

....

....

....

....

....

(iii) Hence calculate the speed of a proton of mass 2.2 m_0.

....

....

....

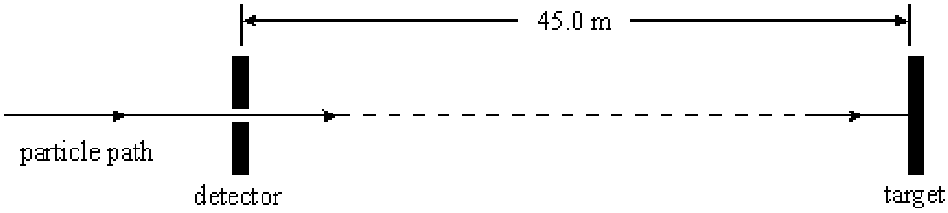
....

....

....

(Total 7 marks)

Q11. A particle passes through a detector and 152 ns later hits a target 45.0 m away from the detector.



(i) Calculate the speed of the particle between the detector and the target.

....

....

(ii) Calculate the transit time of the particle from the detector to the target, in the frame of reference of the particle.

....

....

....

....

....

....

....

(Total 4 marks)

M1. (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 **(1)**
($\therefore$) time taken by light to travel to each mirror unchanged by rotation **(1)**
distance to mirrors is unchanged by rotation **(1)**
($\therefore$) 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]

M2. (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]

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. (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]

M5. (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)**

= 1.9×10^{-27} kg **(1)**

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

= 1.7×10^{10} J **(1)**

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

= 1.5×10^{-10}J **(1)**

6

[10]

M6. (a) (i) d_0 =(speed × time = $1.8 \times 10^8 \times 95 \times 10^{-9}$) = 17(.1) m ✓

1

(ii) d (= $d_0 (1 - v^2/c^2)^{½}$)

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

= 14 m ✓ (or 13.7 m or 13.68 m)

or

$t = t_0 (1 - v^2/c^2)^{-½}$

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

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

2

(b) m (= $m_0 (1 - v^2/c^2)^{-½}$)

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

= 2.09 × 10^{-27} kg ✓

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

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

or correct calculation of $E_0 = m_0c^2$ (= 1.50 × 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]

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)**

$$\therefore\ t = \frac{18 \times 10^{-9}}{(1 - 0.95^2)^{1/2}} = 57(.6) \times 10^{-9}\ \text{s}$$ (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 $t = \frac{t_0}{\sqrt{(1 - v^2/c^2}}$, 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) $10m_0 = m_0\left(1 - \frac{v_2}{c^2}\right)^{-\frac{1}{2}}$ **(1)**

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

v (= 0.995*c*) = 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 → infinity as *v* → *c* **(1)**

[or *m* increases as *v* increases]

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

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

impossible **(1)**

Max 3

[6]

M9. (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 (= $0.994ct = 0.994 \times 3 \times 10^8 \times 7300$)

= 2.2×10^{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]

M10. (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) $\Delta m = \left(\frac{1.8 \times 10^{-10}}{(3 \times 10^8)^2}\right) = 2.0 \times 10^{-27}$ (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)**

= 2.7×10^8 m s^{-1} **(1)**

[7]

M11. (i) $v \left(= \frac{45}{152 \times 10^{-9}} \right) = 2.96 \times 10^{8}$ 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]