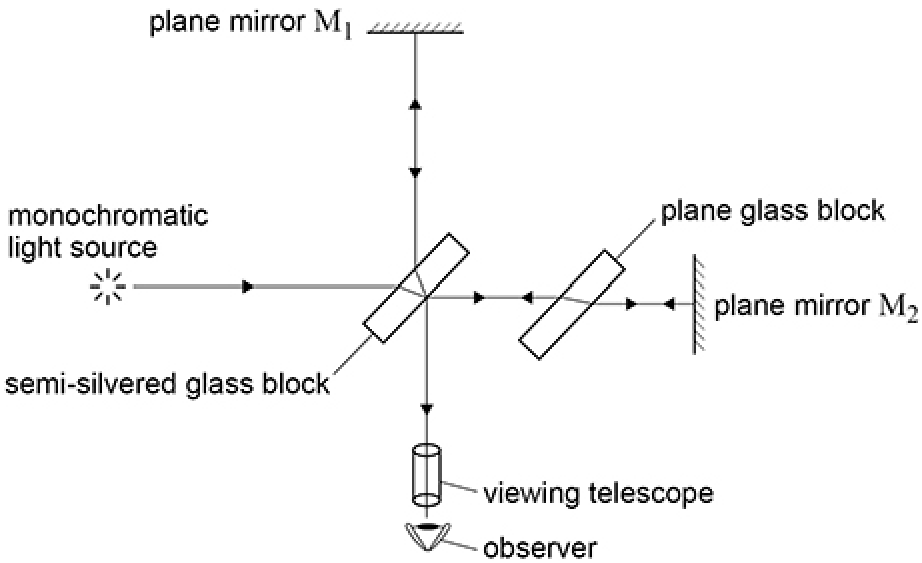
1. The figure below shows the features of a Michelson-Morley interferometer.



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.

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 M1 and M2 , 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

(Total 6 marks)

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.

from formula sheet : total energy of a relativistic object (object moving at a speed close to c)

$$\hookrightarrow E = \frac{m_0 c^2}{\sqrt{1 - \frac{v^2}{c^2}}} \longrightarrow \sqrt{1 - \frac{v^2}{c^2}} = \frac{m_0 c^2}{E} = \frac{1.673 \times 10^{-27} \times (3 \times 10^8)^2}{(3.7 \times 10^9 \times 1.6 \times 10^{-19})} = 0.2543$$

$$1 - \frac{v^2}{c^2} = (0.2543)^2 \longrightarrow \frac{v}{c} = \sqrt{1 - (0.2543)^2} = 0.967$$

proton velocity = ____________________ c

(Total 3 marks)

3. (a) 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.

length contraction: $l = l_0 \sqrt{1 - \frac{v^2}{c^2}} = 2.5 \times 10^3 \times \sqrt{1 - (0.95)^2} = 780.6\,\text{m}$

length measured by external observer.

proper length measured by stationary observer

Here we assume the muon is looking at the second detector as the object moving towards it with a speed of 0.95c!

So the muon is the external observer! And the distance to the detector is the length which appears shorter to the muon!

distance = _______________ m

(2)

(b) 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.

umber 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).

(2)

(c) 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.

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 ✓

(3)
(Total 7 marks)

4. (a) A student models a spacecraft journey that takes one year. The spacecraft travels directly away from an observer at a speed of 1.2×10^7 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.

$$t = \frac{t_0}{\sqrt{1 - v^2/c^2}} = \frac{365}{\sqrt{1 - \frac{(1.2\times10^7)^2}{(3\times10^8)^2}}} = 365.29 \text{ days}$$

The recorded time will be longer (as predicted) ✓
The recorded time will be less than several days longer (as predicted) ✓

(4)

(b) 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.

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 ✓

~~Inertial frames of reference are those which move at a constant velocity relative to each other,~~
therefore a frame that is accelerating or rotating cannot be an inertial frame of reference.

(2)
(Total 6 marks)

5. (a) State what is meant by an inertial frame of reference.

One which moves at constant velocity

(1)

(b) 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 m.
The speed of the particles in the beam is 0.97*c*.

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.

$A = A_0 e^{-\lambda t} \longrightarrow \frac{A}{A_0} = 0.125 = e^{-\lambda(1.55\times10^{-7})} \longrightarrow \ln(0.125) = -\lambda(1.55\times10^{-7})$

$t = \frac{45\,m}{0.97(3\times10^8)} = 1.55\times10^{-7}\,s$ $\quad \ln\left(\frac{A}{A_0}\right) = -\lambda t \longrightarrow \lambda = \longrightarrow \lambda = 13447.55.3\ 1/s$

$T_{1/2} = \frac{\ln 2}{\lambda} = 5.15\times10^{-8}\,s$

$t = \frac{t_0}{\sqrt{1-v^2/c^2}} \longrightarrow t_0 = t\sqrt{1-\frac{v^2}{c^2}} = 5.15\times10^{-8}\times\sqrt{1-0.97^2} = 1.25\times10^{-8}\,s$

half-life = ____________ s

(4)

(c) In calculations involving time dilation, it is important to identify proper time.

Identify the proper time in the calculation in part (b).

The time taken for particle beam to travel between detectors 'measured' in the reference frame of particle beam ✓

part(b) alternative method:

distance to second detector appears shorter to particles:

$l = l_0\sqrt{1-v^2/c^2} = 45\times\sqrt{1-0.97^2} = 10.9\,m$

l_0: proper length in eye of stationary observer! ↳ particle

Particle's speed does not depend on observer!

time taken in the eye of particles $= \frac{10.9}{0.97\times3\times10^8} = 3.76\times10^{-8}\,s$

How many half-lives to get to 12.5% : 1 → 50% 2 → 25% 3 → 12.5%

So $3.76\times10^{-8}\,s$ is 3 half-lives $\longrightarrow T_{1/2} = \frac{3.76\times10^{-8}}{3} = 1.25\times10^{-8}\,s$ ✓

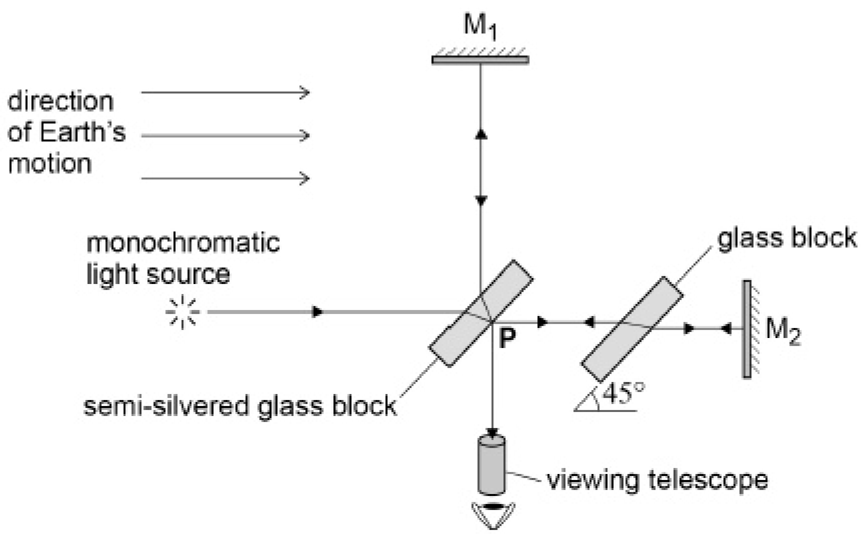
(1)

(Total 6 marks)

6. **Figure 1** 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 1



It was predicted that when the interferometer was rotated through 90° the fringe pattern would shift by 0.4 of the fringe spacing.

(a) 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.

(Explanation of how shift was expected)
1. PM2 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 M2 and back to P would be greater than the time taken from P to M1 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
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

(6)

(b) The Michelson-Morley experiment provides evidence for one of the postulates of Einstein's theory of special relativity.

State this postulate.

Invariance of the speed of light in free space/vacuum

Speed of light the same in free space

(1)

(c) State the other postulate of Einstein's theory of special relativity.

Invariance of the speed of light in free space/vacuum
Speed of light the same in free space
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 (b) and (c) are correct but reversed

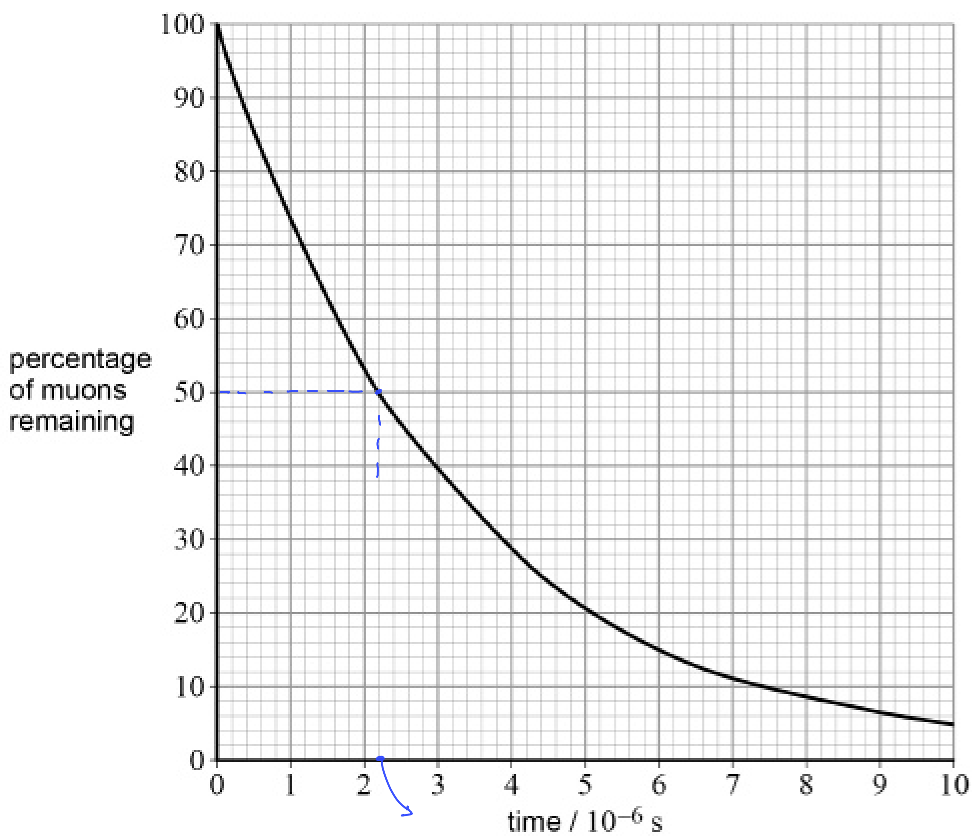
(1)

(d) 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 2 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 2



$T_{1/2} = 2.2 \times 10^{-6}$ s in frame of muon

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

Determine the percentage of muons that reach the detector.

1.559538×10^{-5} s

half-life for an external observer: $t = \dfrac{t_0}{\sqrt{1 - v^2/c^2}} = \dfrac{2.2 \times 10^{-6}}{\sqrt{1 - 0.99^2}} = 1.56 \times 10^{-5}$ s

$t = \dfrac{1310}{0.99 \times 3 \times 10^8} = 4.41 \times 10^{-6}$ s

No. of half-lives $= \dfrac{4.41 \times 10^{-6}}{1.56 \times 10^{-5}} = 0.283$

percentage = ____________________ %

(4)

(Total 12 marks)

remaining $= N \times \left(\frac{1}{2}\right)^{0.283} = 82.2\%$