AQA A-LEVEL PHYSICS · 7408

# PHYSICS



EXAM QUESTION PACK

## 3.12.3 SPECIAL RELATIVITY

| SCORE | PERCENTAGE |
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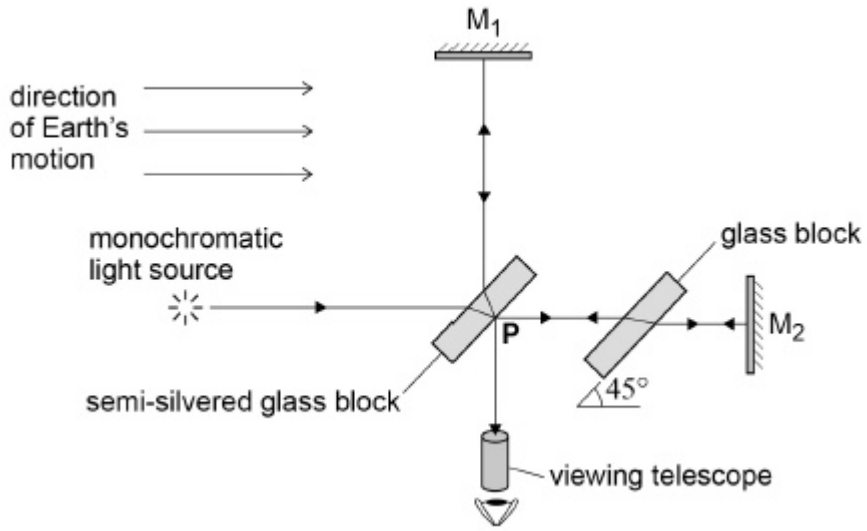
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## Q1.

**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.



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**(6)**

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

State this postulate.

**(1)**

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

**(1)**

(d) One consequence of the special theory of relativity is length contraction.

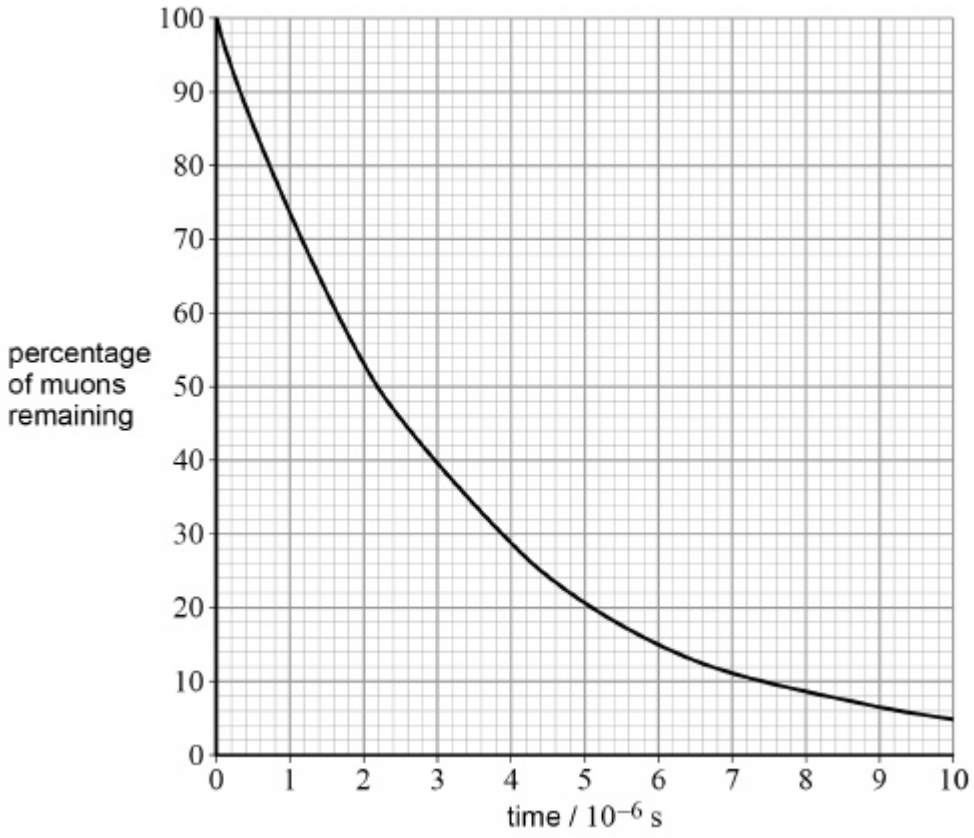
Experimental evidence for length contraction is provided by the decay of muons produced in the atmosphere by cosmic rays.

**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**



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

Determine the percentage of muons that reach the detector.

percentage = _____ %

**(4)**

**(Total 12 marks)**

## Q2.

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

_____



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**(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.

**(2)**

**(Total 6 marks)**

## Q3.

Cosmic rays detected on a spacecraft are protons with a total energy of $3.7 \times 10^9$ eV.

Calculate the velocity of the protons as a fraction of the speed of light.

proton velocity = _____ $c$

**(Total 3 marks)**

## Q4.



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(a) Bertozzi's experiment was designed to test the relationship between the kinetic energy of an electron and its speed as predicted by the theory of special relativity.

Describe Bertozzi's experiment.

Your answer should include:
- a diagram of the experimental arrangement
- details of how the kinetic energy and the speed were measured.

**(6)**

(b) A scientist conducts an experiment similar to Bertozzi's experiment and reports that when the electron speed is $2.93 \times 10^8$ m $s^{-1}$ the measured kinetic energy is 2.4 MeV.

Determine whether these data are consistent with the result expected using the theory of special relativity.

**(4)**

**(Total 10 marks)**



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**Q6.**

(a) The theory of special relativity is based on two postulates. One of these postulates is that the speed of light in free space is invariant.
State the other postulate.

_____

_____

**(1)**

(b) An electron in the Stanford linear accelerator is accelerated to an energy of 24.0 GeV.

(i) An electron travelling with this energy has a velocity $v$.

Show that the value of $\left(1-\frac{v^2}{c^2}\right)^{\frac{1}{2}}$ is about $2.1 \times 10^{-5}$.

**(3)**

(ii) The Stanford linear accelerator has a length of 3.0 km. Assume that the electron travels for the full length of the accelerator with an energy of 24 GeV. Calculate the length, in m, of the accelerator in the reference frame of the electron.

length of accelerator = _____ m

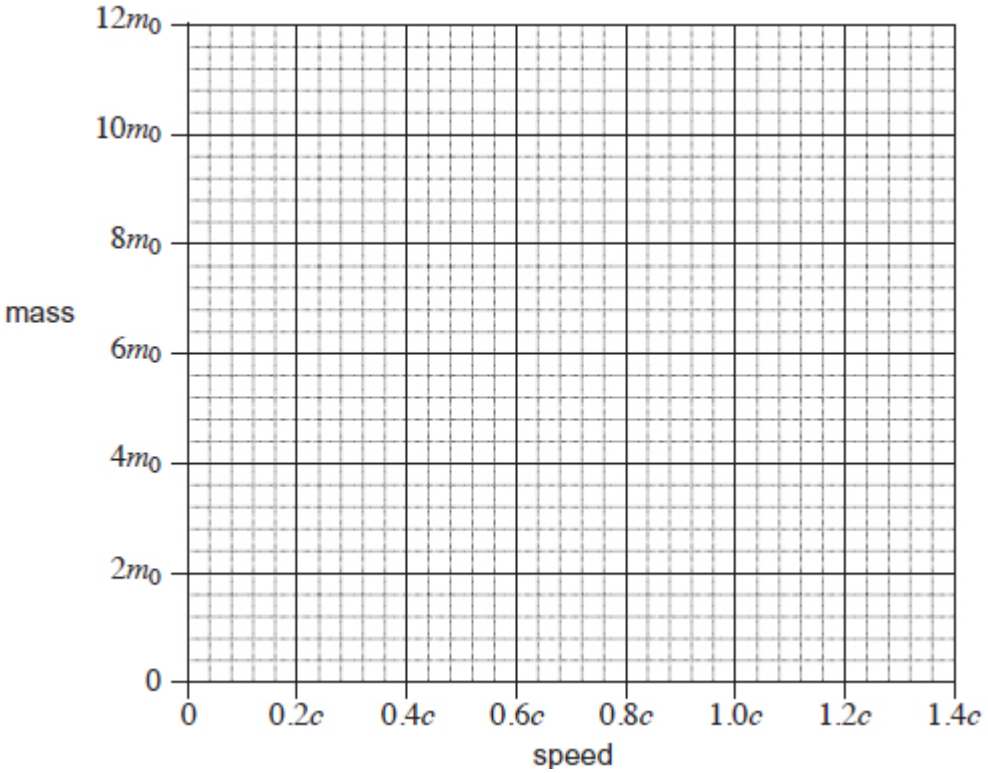
**(1)**

(c) Draw a graph to show how the relativistic mass of an electron varies with speed as it is accelerated from rest.

Rest mass of an electron = $m_0$



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**(2)**

**(Total 7 marks)**

## Q7.

Cosmic rays mostly consist of high-energy protons. These protons can collide with atomic nuclei in the Earth's upper atmosphere producing pions ($\pi^-$). Pions are unstable and decay into high-energy muons ($\mu^-$).

(a) (i) Which of the following is the particle group for pions ($\pi^-$)?

Tick (✓) the correct answer.

Baryons ☐

Leptons ☐

Mesons ☐

Photons ☐

**(1)**

(ii) Complete the equation for the decay of a pion ($\pi^-$).

$$\pi^- \longrightarrow \mu^- + _____$$

**(1)**



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(b) $2.5 \times 10^8$ muons are created simultaneously above the EarthÙs surface. These muons are unstable and have a half-life of 2.2 μs. They are created at a height of 10.7 km and travel towards the Earth's surface with a constant vertical velocity of $2.85 \times 10^8$ m $s^{-1}$.

(i) Show that, for the reference frame of an observer on Earth, the time taken for the muons to reach the Earth's surface is approximately 17 muon half-lives.

**(2)**

(ii) Estimate the number of these muons that an observer on Earth would expect to remain after 17 half-lives.

number _____

**(2)**

(iii) The number of muons that reach the Earth's surface is considerably different from the estimated number in part **(b)(ii)**.

Identify the theory that explains the difference between the estimated and observed number of muons.

_____

**(1)**

(iv) Outline why the number of muons that actually reach the Earth's surface is different from the estimated number in part **(b)(ii)**.

_____

_____

_____

**(1)**

(v) Calculate, for the reference frame of a muon, the time taken for the muons to travel this distance.

time _____ s

**(3)**

(vi) Calculate the number of muons that remain at the end of the time interval calculated in part **(b)(v)**.



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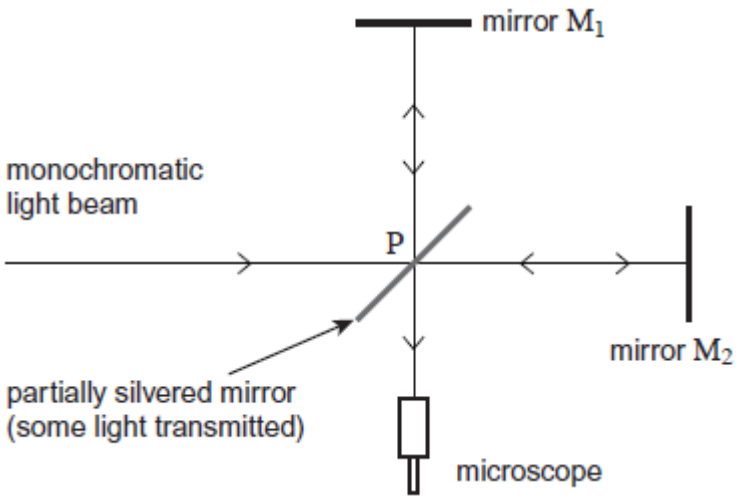
number _____

**(3)**

**(Total 14 marks)**

## Q8.

The diagram shows the paths of light rays through a simplified version of the apparatus used by Michelson and Morley.




In the apparatus, light waves reflected by the mirrors $M_1$ and $M_2$, meet at $P$ so that they superpose and produce interference fringes. These are observed using the microscope.

Michelson and Morley predicted that the fringes would shift when the apparatus was rotated through 90°. They thought that this shift would enable them to measure the speed of the Earth through a substance, called the aether, that was thought to fill space.

(a) Explain why Michelson and Morley expected that the fringe positions would shift when the apparatus was rotated through 90°.

_____

_____

_____

_____

_____

_____

**(2)**

(b) In their apparatus they made the distances $PM_1$ and $PM_2$ the same and equal to $d$. They used light of wavelength ($\lambda$) about 550 nm and knew that the speed of light $c$ was $3.0 \times 10^8$ m s$^{-1}$. Using known astronomical data, they calculated the speed $v$ at which they thought the Earth moved through the aether. They were then able to predict that when the apparatus was rotated through 90° the fringes should shift by a distance $0.4f$, where $f$ was the fringe spacing.

(i) To determine $v$, Michelson and Morley assumed that the Sun was stationary



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with respect to the aether as the Earth moved through it.
Suggest, using this assumption, how the speed $v$ of the Earth through the aether could be determined. You do not need to do the calculation.

_____

_____

_____

_____

**(1)**

(ii) Michelson and Morley calculated $v$ to be $3.0 \times 10^4$ m s$^{-1}$.
They worked out $\Delta f$, the magnitude of the expected shift of the fringes, using the

formula $\Delta f = \frac{2v^2 d}{c^2 \lambda} f$.

Calculate the distance $d$ they used in their experiment.

$d$ = _____ m

**(1)**

(c) Although a shift of 0.4 $f$ was easily detectable, no shift was observed. Explain what this null result demonstrated and its significance for Einstein in his special theory of relativity.

_____

_____

_____

_____

_____

_____

**(2)**

**(Total 6 marks)**

## Q9.



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A muon is an unstable particle produced by cosmic rays in the Earth's atmosphere. Muons that are produced at a height of 10.7 km above the Earth's surface, travel at a speed of $0.996c$ toward Earth, where $c$ is the speed of light. In the frame of reference of the muons, the muons have a half-life of $1.60 \times 10^{-6}$ s.

(a) (i) Calculate how many muons will reach the Earth's surface for every 1000 that are produced at a height of 10.7 km.

number of muons _____

**(3)**

(ii) Which of the following statements is correct? Tick (✓) the correct answer.

| | ✓if correct |
|---|---|
| For an observer in a laboratory on Earth, the distance travelled by a muon that reaches the Earth is greater than the distance travelled by a muon in its frame of reference | |
| For an observer in a laboratory on Earth, time passes more slowly than it does for a muon in its frame of reference | |
| For an observer in a laboratory on Earth, the probability of a muon decaying each second is lower than it is for a muon in its frame of reference | |

**(1)**

(b) (i) Show that the total energy of an electron that has been accelerated to a speed of $0.98c$ is about $4 \times 10^{-13}$ J.

**(2)**



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(ii) The total energy of an electron travelling at a speed of $0.97c$ is $3.37 \times 10^{-13}$ J.

Calculate the potential difference required to accelerate an electron from a speed of $0.97c$ to a speed of $0.98c$.

potential difference = _____ V

**(1)**

**(Total 7 marks)**



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