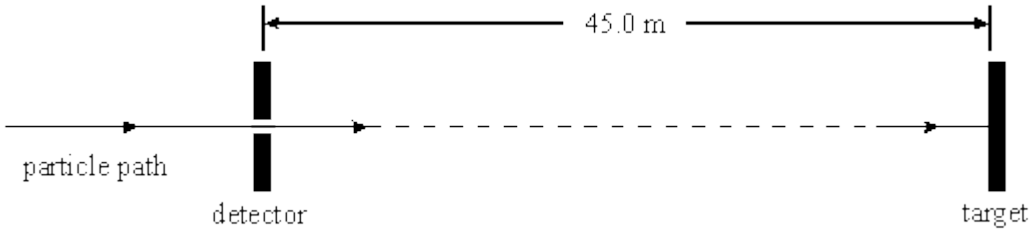
1 A particle passes through a detector and 152 ns later hits a target 45.0 m away from the detector.



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

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

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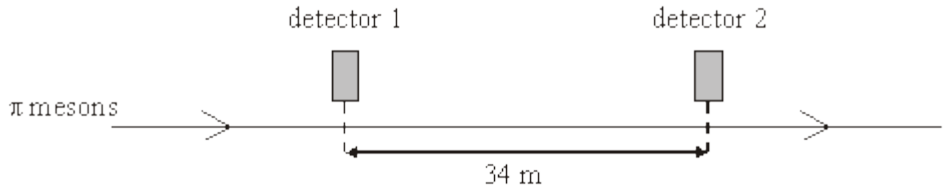
(Total 4 marks)

2 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.

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(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.

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(Total 5 marks)

3 (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.

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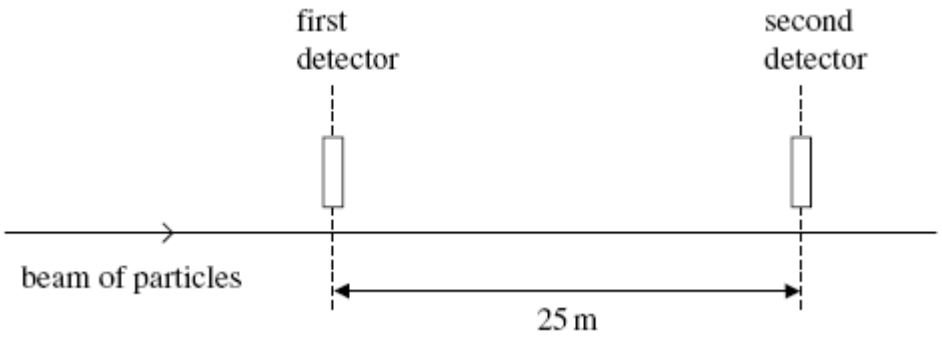
(1)

(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)

4 (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.

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

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(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.

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(3)
(Total 7 marks)

5 (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.

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(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.

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(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.

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(5)
(Total 7 marks)

6 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 0.996 c toward Earth, where c is the speed of light. In the frame of reference of the muons, the muons have a half-life of 1.60×10^{-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 4×10^{-13} J.

(2)

(ii) The total energy of an electron travelling at a speed of $0.97c$ is 3.37×10^{-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)

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

(a) Explain what is meant by this postulate.

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(1)

(b) State the other postulate.

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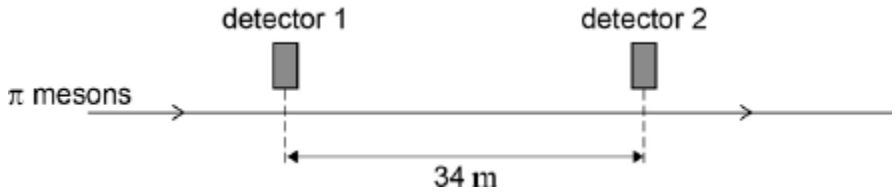
(1)

(c) Two detectors are measured to be 34 m apart by an observer in a stationary frame of reference. A beam of π mesons travel in a straight line at a speed of 0.95 c past the two detectors, as shown in the figure below.



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

time = ...

(1)

(d) π mesons are unstable and decay with a half-life of 18 ns.

It is found in experiments that approximately 75% of the π mesons that pass the first detector decay before reaching the second detector.

Show how this provides evidence to support the theory of special relativity. In your answer compare the percentage expected by the laboratory observer with and without application of the theory of special relativity.

(5)
(Total 8 marks)

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

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

Tick (✓) the correct answer.

Baryons ☐

Leptons ☐

Mesons ☐

Photons ☐

(1)

(ii) Complete the equation for the decay of a pion (π^-).

$$\pi^- \longrightarrow \mu^- + \text{.....}$$

(1)

(b) 2.5×10^8 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 2.85×10^8 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.

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(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)**.

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(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)**.

number .....

(3)

(Total 14 marks)

9 (a) Michelson and Morley attempted to detect absolute motion by investigating whether or not the speed of light in a direction parallel to the Earth's motion differs from the speed of light perpendicular to the Earth's motion.

Discuss what resulted from this experiment and what was concluded.

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(3)

(b) In a science fiction story, a space rocket left the Earth in 2066 and travelled out of the Solar System at a speed of $0.80c$, where c is the speed of light in vacuo, to a star 16 light years from the Earth.

(i) How many years, in the frame of reference of the Earth, did the spacecraft take to reach the star?

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(ii) What was the distance, in the frame of reference of the spacecraft, between the Earth and the star?

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(iii) A member of the crew was 21 years old on leaving the Earth. How old was this person on arrival at the star?

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(6)
(Total 9 marks)

10 (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 statement.

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(ii) What is the other postulate?

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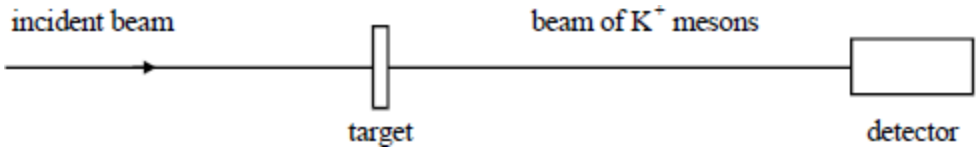
(3)

(b) K^+ mesons are sub-atomic particles of half-life 86 ns when at rest. In an accelerator experiment, a beam of K^+ mesons travelling at a speed of $0.95c$ is created, where c is the speed of light.



(i) Calculate the half-life of the K^+ mesons in the beam measured in the laboratory frame of reference.

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(ii) What is the greatest distance that a detector could be sited from the point of production of the K^+ mesons to detect at least 25% of the K^+ mesons produced?

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(6)
(Total 9 marks)