**Q1.** 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)**

(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)**

**Q2.** 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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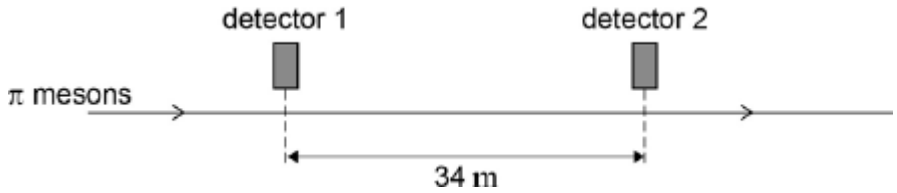
**(1)**

(c) Two detectors are measured to be 34 m apart by an observer in a stationary frame of reference. A beam of $\pi$ 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 $\pi$ meson to travel between the two detectors.

time = .....

**(1)**

(d) $\pi$ mesons are unstable and decay with a half-life of 18 ns.
It is found in experiments that approximately 75% of the $\pi$ 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)**

**Q3.** (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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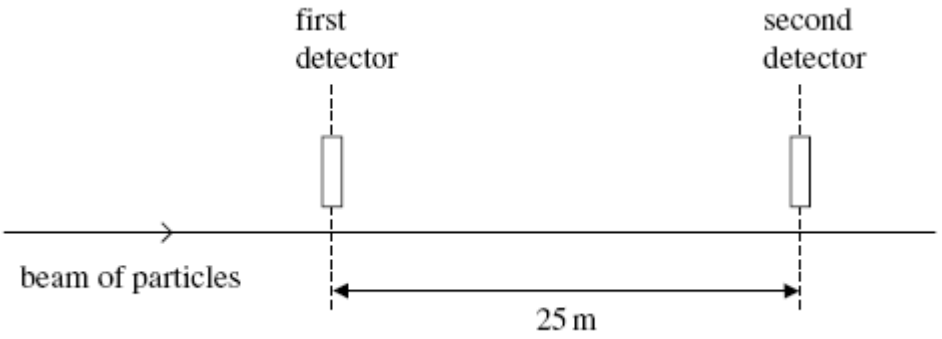
**(1)**

(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.



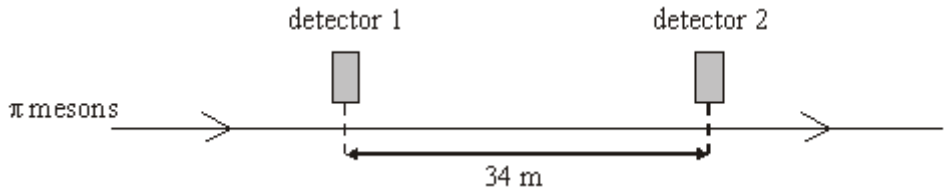

The particles are unstable and the intensity of the beam at the second detector is a quarter of the intensity at the first detector.

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

answer = ..... s

**(4)**
**(Total 5 marks)**

**Q4.** $\pi$ 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 $\pi$ meson to travel between the two detectors.

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

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**(Total 5 marks)**

**Q5.** (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)**