In an experiment done at Massachusetts Institute of Technology, electrons were given a series of known kinetic energies (KE) by accelerating them across a range of electric potentials, and measuring the electron's velocity, v, for each value of KE.

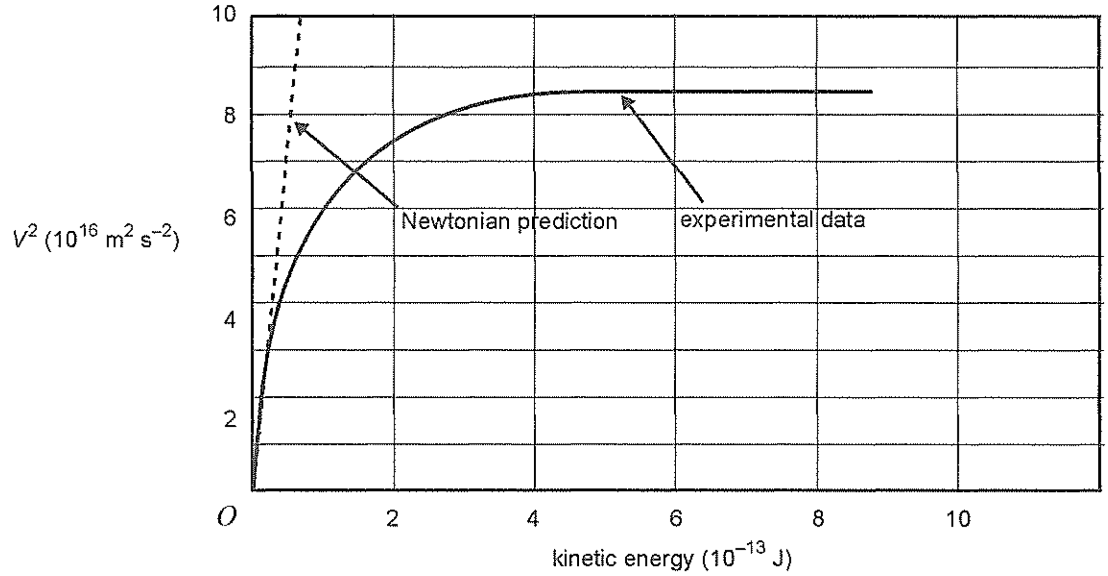

Figure 2

The solid curve in Figure 2 shows the variation of v^2 as a function of KE, as measured in the experiment. The dashed curve is the value of v^2 calculated using the Newtonian expression for kinetic energy.

Question 4

According to Newtonian mechanics, what would be the **speed** of an electron with a KE of 10×10^{-13} J?
The mass of an electron is 9.1×10^{-31} kg.

m s^{-1}

2 marks

Question 5

Using the experimental data shown in Figure 2, indicate in the box provided which one of the statements below gives the best estimate of the **measured speed** of an electron with a KE of 10×10^{-13} J.

A. It is approximately 9×10^{16} m s^{-1}.

B. It is approximately 3×10^{8} m s^{-1}.

C. It is approximately 9.1×10^{-31} m s^{-1}.

D. It cannot be estimated.

2 marks

In order to explain the propagation of a light wave, it was assumed in the late 19th century that all of space was filled with 'ether', which not only provided a medium for the wave, but also an absolute spatial reference frame. In order to check this, Michelson and Morley performed their famous experiment. A simplified plan of their equipment is shown below in Figure 3. The arrows show the direction in which the light is travelling. The intensity at the detector relied on interference between the light travelling the different paths. The apparatus was mounted on a rigid stand so that it could be rotated.

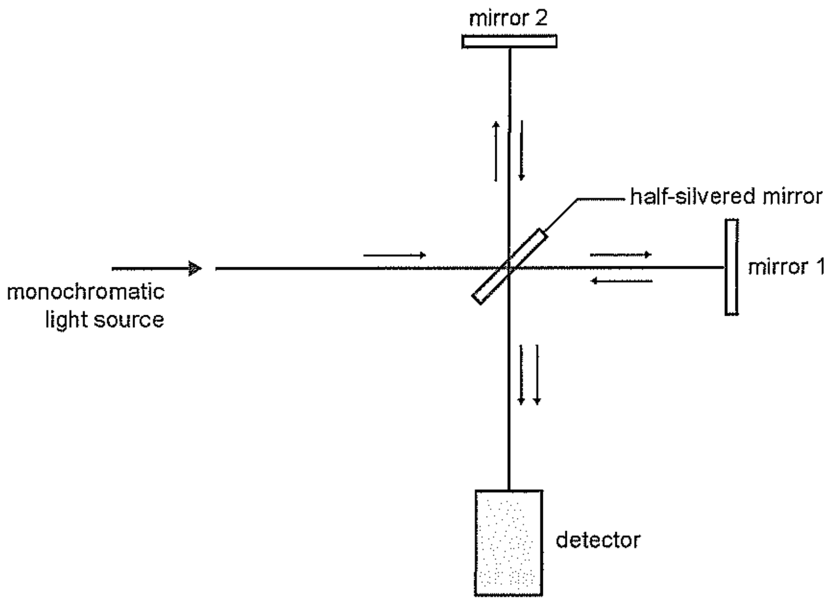

Figure 3

Question 6

Which one of the statements (**A.–D.**) specifies the critical basis of the apparatus?

A. The half-silvered mirror must reflect exactly half the light.

B. Mirror 1 and mirror 2 must be identical.

C. The distance travelled by light using either path must be equal.

D. The components must not move relative to each other.

2 marks

The apparatus was set up so that the light travelling towards mirror 2 was travelling perpendicular to the motion of Earth around the Sun, and the light travelling towards mirror 1 was in the direction of Earth's motion in its orbit. The measurement was then repeated with the apparatus turned through an angle of 90°.

Question 7

In the space below explain why this was done, and what results Michelson and Morley obtained.

3 marks

Question 8

Jason and Kylie are sitting at the northern and southern ends respectively of a train carriage travelling north at a high speed. Each holds a torch that they turn on and off. Harold is standing on a platform beside the train. As the midpoint of the carriage passes Harold, he observes simultaneous light flashes from both Jason and Kylie.

Which one of the following statements is true?

A. To an observer inside the carriage, located at its midpoint, Jason and Kylie turned on their torches at the same time.

B. To an observer inside the carriage, located at its midpoint, Jason turned on his torch before Kylie.

C. To an observer inside the carriage, located at the midpoint, Kylie turned on her torch before Jason.

D. It does not make any sense to ask in which order Jason and Kylie turned on their torches, because Einstein showed that time is relative.

2 marks

The electron accelerator at Stanford University is 3.2 km long (Figure 4). Electrons reach a velocity of 0.9999995 c, which means the Lorentz factor is 1000.

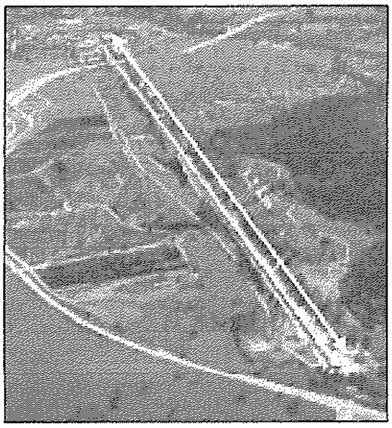

Figure 4

Question 9

For an electron travelling the length of the accelerator at this velocity, what would be the length of the accelerator in the electron's reference frame?

m

3 marks

Question 10

As measured by a scientist at the accelerator laboratory, how long would the electron take to travel the length of the accelerator?

s

2 marks

Question 11

How long would the electron measure its time of travel to be?

s

3 marks

One of the basic particles of nature is the *tau meson*, which can be created using beams of high energy particles from an accelerator. When created, the tau meson has a very high velocity of 0.998749 c, which means it has a Lorentz factor of 20. However it only exists for a period of 6.10×10^{-12} s as measured by the scientists at the accelerator laboratory. After this time it decays into two other particles. During this time it is observed to travel a distance *d*. Figure 3 shows the creation and decay of the tau meson in the reference frame of the scientists.

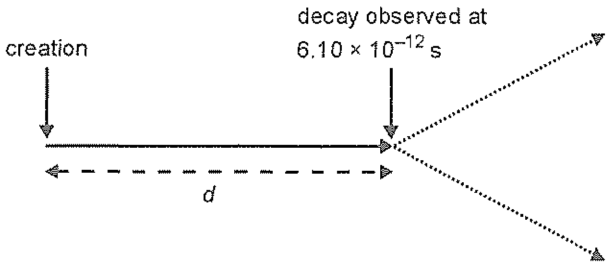

Figure 3

Question 5
What is the lifetime of the tau meson as measured in its own frame of reference?

[s]

3 marks

Question 6
What is the distance *d* in Figure 3, as measured by the scientists?

[m]

2 marks

Question 7
As measured in the reference frame of the tau meson, what would be the distance *d*?

[m]

3 marks

2005

According to Einstein's special theory of relativity, mass and energy are related. The mass of an electron when it is at rest is 9.1×10^{-31} kg.

Question 8

Show that this is equivalent to an energy of 8.20×10^{-14} J.

2 marks

The electron accelerator at the ARPANSA laboratory at Yallambie, near Melbourne, can accelerate an electron to a speed such that its mass increases **by a factor of 22**.

Question 9

What is the value of the Lorentz factor for an electron as it leaves the accelerator?

2 marks

Question 10

Which of the following (**A–D**) gives the kinetic energy of the electron as it leaves the accelerator?

A. 8.20×10^{-15} J

B. 1.72×10^{-12} J

C. 1.80×10^{-13} J

D. 5.11×10^{-6} J

2 marks

END OF DETAILED STUDY 1

Muons are elementary particles created in the upper atmosphere by cosmic rays. They are unstable, and decay with a half-life of 2.2 μs (2.2×10^{-6} s) when measured at rest. This means that in the reference frame of the muons, half of them decay in each time interval of 2.2 μs.

In an experiment, 1000 muons with a velocity of 0.995c were observed to pass the top of a mountain of height 2627 m. Experimenters measured the number of these reaching ground level.

The experimenters calculated the time that a muon would take to travel from the top of the mountain to the ground. The calculated value was much longer than the muon half-life. Thus the experimenters expected that only a few muons should reach the ground. In fact they detected many more than expected. The reason for the difference is that, relative to the experimenters, the muons were moving at close to the speed of light, and their half-life, **as measured by the experimenters**, increased.

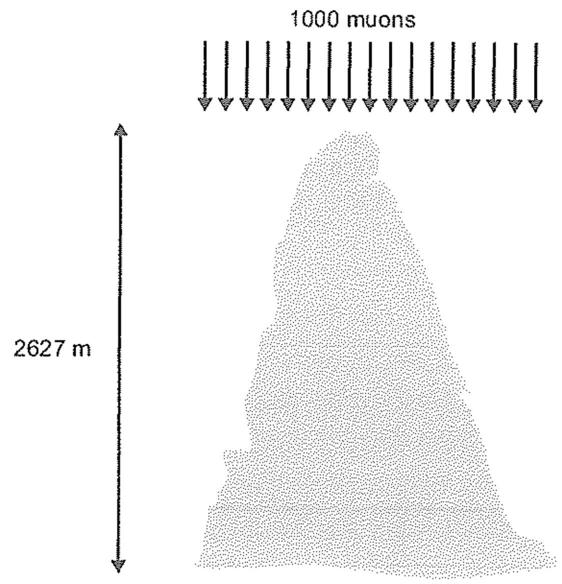

Figure 4

Question 7

Show that the lifetime of the moving muons, as measured from the ground, is approximately 22 μs.

3 marks

From their reference frame, the muons see the ground rushing upwards at a speed of 0.995c.

Question 8

What would be the height of the mountain as measured by the muons?

m

2 marks

Relativistic effects are not easily detectable in everyday situations.

Question 9

At what speed would an object have to be moving for a change of 1% in its length to be observed?

$m\ s^{-1}$

3 marks

Use the following information to answer Questions 3 and 4.

Figure 2 below shows Fred in a futuristic train travelling at constant relativistic speed in an easterly direction in a straight line. Fred is halfway between two people, Alan and Bob, who are at opposite ends of the carriage. The train passes a platform. Nancy is standing on the platform.

At the instant that Fred and Nancy are directly opposite each other, Fred sees both Alan and Bob strike matches simultaneously.

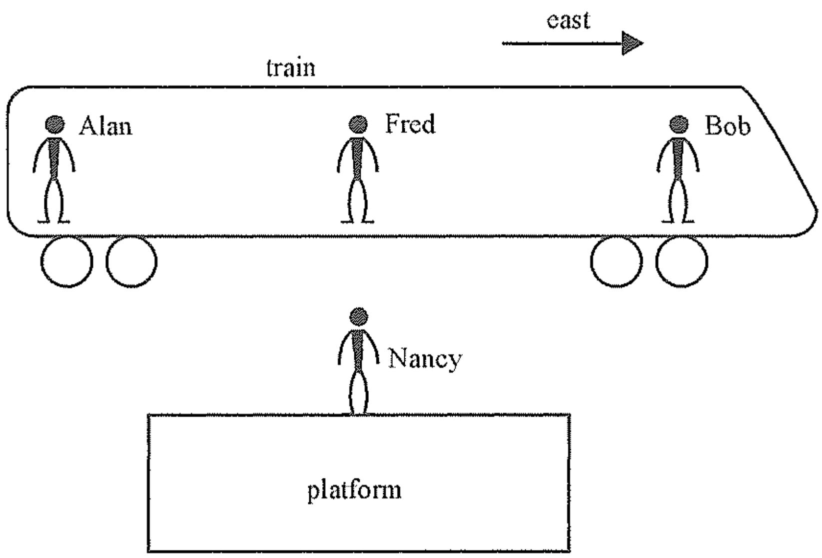

Figure 2

Question 3

Which one of the following best describes how Nancy sees these two events?

A. Nancy sees the light from Alan first.

B. Nancy sees the light from Bob first.

C. Nancy sees the light from both simultaneously, because both are at equal distances from her when they light the matches.

D. Nancy sees the light from both simultaneously, because special relativity requires that light travels at the same speed in all frames of reference.

Question 4

Fred measures the carriage he is travelling in to be 20 m long. Nancy has measured the platform she is standing on to be 10 m long. The train rushes past at such a speed that Nancy sees the carriage and the platform to be the same length.

How fast was the train moving?

A. 0.50 c

B. 0.75 c

C. 0.87 c

D. 0.97 c

Question 6

Michelson and Morley performed an experiment to measure the speed of light with respect to the ether. They believed that Earth moved in its orbit with speed v relative to the ether. They believed there should be a difference in the **measured** speed of light depending on whether it was measured parallel or perpendicular to the direction of Earth's movement through the ether.

The Michelson–Morley experiment found the ratio of

$$\frac{\text{the speed of light measured parallel to the Earth's motion through the ether}}{\text{the speed of light measured perpendicular to the Earth's motion through the ether}}$$

to be

A. slightly less than one.

B. equal to one.

C. slightly greater than one.

D. significantly greater than one.

Question 7

In a nuclear reactor, some mass is converted into energy.

Which one of the following is the best approximation to the total energy released when 1 kg of mass is totally converted into energy?

A. 10^5 J

B. 10^9 J

C. 10^{13} J

D. 10^{17} J

Question 8

According to Einstein's special theory of relativity, the relativistic mass, m, of a body of rest mass m_0, depends on its speed.

Which one of the curves in Figure 2 best shows how the relativistic mass varies with speed?

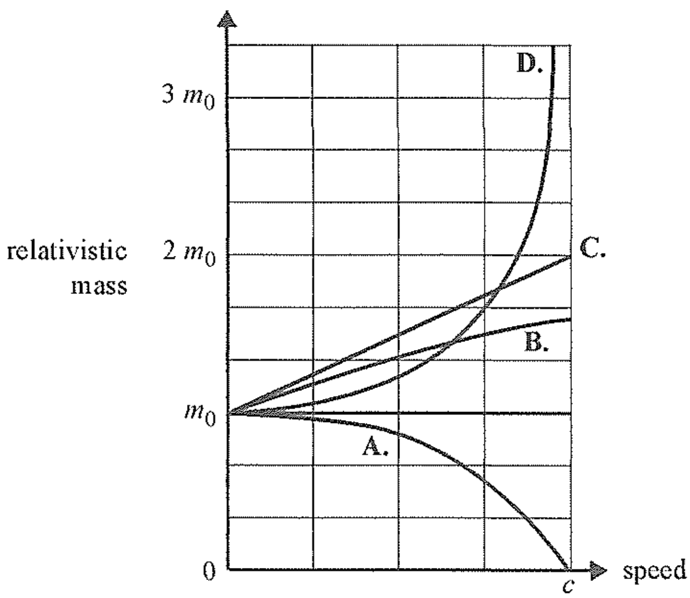

Figure 2

Question 11

Which one of the following is closest to the work that must be done on a proton to increase its speed from zero to 0.9 c, that is $\gamma = 2.29$? (Take m_0 for the proton = 1.67×10^{-27} kg.)

A. 1.9×10^{-10} J

B. 4.0×10^{-20} J

C. 3.5×10^{-11} J

D. 1.7×10^{-27} J

Question 12

In science fiction, spacecraft sometimes travel at speeds greater than the speed of light.

According to Einstein's special theory of relativity, this is not possible because

A. this would require time travel into the past.

B. when an object approaches the speed of light, the rest mass tends towards zero.

C. when an object approaches the speed of light, the value of γ tends towards zero.

D. when an object approaches the speed of light, its relativistic mass, m, approaches infinity.

Question 13

Which one of the following statements is the best statement about inertial frames of reference?

A. Inertial frames must be stationary.

B. Inertial frames must be accelerating.

C. The laws of physics have the same form in all inertial frames.

D. Inertial frames cannot be moving at close to the speed of light.

Detailed study 1 – Einstein's special relativity

Question 1

On a planet a long way away, a racing car is moving at high speed ($0.9c$) along a straight track. It is heading straight for a post. Jim is standing next to the post. The situation is shown in Figure 1.

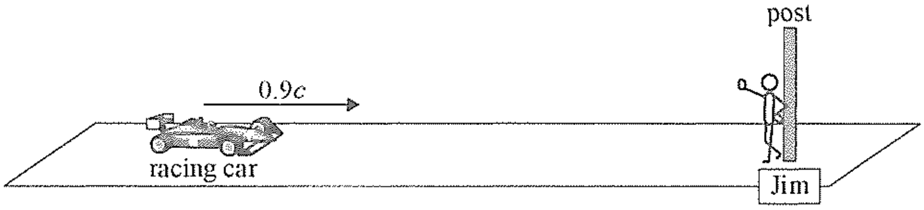

Figure 1

When the racing car is 1.00 km from the post (as measured by Jim), the driver sends a flash of light from the car.

Which of the following is closest to the time that the flash of light takes to reach the post (as measured by Jim)?

A. 1.5 microseconds

B. 1.8 microseconds

C. 3.3 microseconds

D. 3.7 microseconds

Question 2

The driver of the racing car, Susanna, measures the distance between herself and the post at exactly the same time that she sends the flash of light.

Which one of the following is closest to the distance that she measures?

A. 0.44 km

B. 0.90 km

C. 1.00 km

D. 2.29 km

Question 3

On another occasion, Vicky observes the racing car. She is standing exactly midway between two posts, A and B. At the instant the car passes her, the driver sends simultaneous flashes of light forwards and backwards towards the posts. The car is travelling at $0.9c$ towards post B. The arrangement is shown in Figure 2.

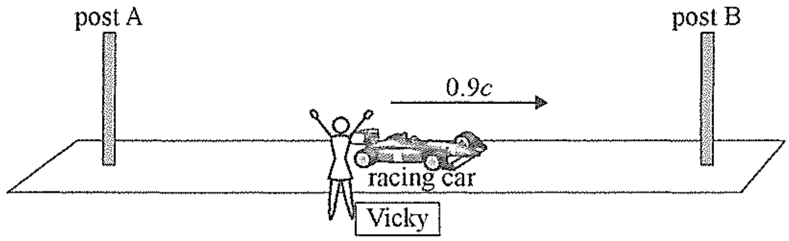

Figure 2

Which one of the following best describes when the flashes of light reach the posts, as observed by Vicky?

A. Post A receives the flash of light first.

B. Post B receives the flash of light first.

C. Post A and Post B receive a flash of light at the same time.

D. It is not possible to predict which receives a flash of light first.

Question 4

Which one of the following is the best description of the **proper length** of an object travelling with constant velocity?

A. The length when measured by any observer at the same location.

B. The length when measured by an observer at rest relative to the object.

C. The length when both ends of the object are measured at the same time.

D. The length when measured with a proper standard measuring stick.

Question 5

Two physics students are conducting accurate experiments to test Newton's second law of motion ($\Sigma F = ma$). Each student is in a windowless railway carriage. One carriage (carriage A) is moving at a constant velocity of $0.9c$. The other carriage (carriage B) is moving at 10 m s^{-1} and decelerating.

Which one of the following best describes the likely results of their experiments?

A. Only the experiment in carriage A confirms Newton's second law of motion.

B. Only the experiment in carriage B confirms Newton's second law of motion.

C. Neither experiment confirms Newton's second law of motion.

D. Both experiments confirm Newton's second law of motion.

The following information relates to Questions 6–8.

A robot is heading radially towards the surface of a planet in the *Hoth* system at a constant speed of $0.85c$. Observers on the surface of the planet observe it at a time when it is a distance x above the surface in their reference frame. The observers calculate the time that the robot will take to reach the surface of the planet as 784 microseconds.

The situation is shown in Figure 3.

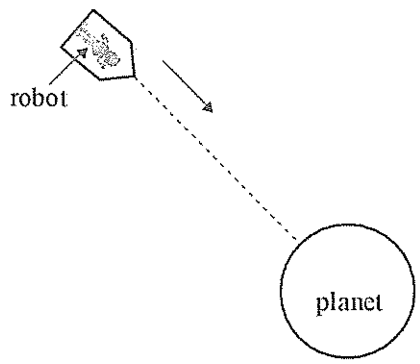

Figure 3

Question 6

Which one of the following is closest to the distance x?

A. 105 km

B. 200 km

C. 235 km

D. 380 km

Question 7

Which one of the following is the best estimate of the time, as measured by the **robot**, for it to reach the surface of the planet?

A. 413 microseconds

B. 666 microseconds

C. 784 microseconds

D. 1488 microseconds

Question 8

Which one of the following best describes the time of the robot's descent to the planet surface as measured by the robot, and the time as measured by the observers on the surface of the planet?

A. They are both measurements of proper time in their own reference frames.

B. Neither are measures of proper time.

C. Only the observers measure the proper time.

D. Only the robot measures the proper time.

Question 9

Which one of the following best describes what follows directly from the measurements of the Michelson–Morley experiment?

A. The speed of light near the surface of Earth depends on the direction in which it is measured travelling.

B. The speed of light near the surface of Earth is the same in all directions.

C. Earth travels through a stationary ether.

D. The ether may exist, but it is not detectable.

Question 10

Muons and antimuons are anti-particles of each other. They have the same mass. When a muon meets an antimuon, both are destroyed and two photons (gamma rays) are formed. If the two particles are effectively stationary, then the two photons have a **total** energy of 3.38×10^{-11} J.

Using this data, which one of the following is closest to the mass of a single muon?

A. 3.76×10^{-28} kg

B. 1.88×10^{-28} kg

C. 1.13×10^{-19} kg

D. 5.64×10^{-19} kg

Question 11

In a particle accelerator, an alpha particle of mass 6.64424×10^{-27} kg is accelerated from rest to high speed. The total work done on the alpha particle is equal to 7.714×10^{-10} J.

Which one of the following is closest to its final speed?

A. $0.90c$

B. $0.95c$

C. $0.85c$

D. $0.80c$

Detailed study 1 – Einstein's special relativity

Question 1

An experiment is done where two protons with very high kinetic energy collide in order to try to create a single stationary 'Higgs' particle.

Each proton in the reaction has a kinetic energy of 1.1×10^{-6} J. No other particles are produced in the reaction and the protons will not exist after the production of the Higgs particle.

The proton rest mass is equal to 1.6726×10^{-27} kg.

Which of the following options is the best estimate of the mass of the Higgs particle?

A. 1.2×10^{-23} kg

B. 2.4×10^{-23} kg

C. 3.3×10^{-27} kg

D. 1.7×10^{-27} kg

Question 2

According to the theory of special relativity, the mass, m, of a particle, and its total energy, E, are equivalent. The relationship is

$$E = mc^2 \text{ where } m = \gamma m_o, \text{ and } \gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$

The amount of energy required to increase the speed of an electron from $0.18c$ to $0.19c$ is 0.004 J. By contrast, the amount of energy required to increase this electron's speed by the same amount ($0.01c$) from $0.98c$ to $0.99c$ is 27.7 J.

Which of the following best explains why much more energy is required to produce the same change in speed for the electron when it is moving at the higher speed?

A. The rest mass (m_0) of the electron is not a constant but depends on the speed v.

B. The electron mass-energy is proportional to v, so it is more massive at high speed.

C. Because $E = \frac{1}{2} mv^2$, the larger v, the more energy is required to increase it further.

D. The total mass-energy of the electron depends on γ, which increases rapidly as v approaches c.

Question 3

When stationary, a proton has a rest mass-energy of 1.50×10^{-10} J.

A proton is accelerated from a speed with $\gamma = 1.05$ to a speed with $\gamma = 1.10$.

Which of the following is closest to the work done on the proton during its acceleration from the first speed to the second speed?

A. 2.9×10^{6} J

B. 3.2×10^{-10} J

C. 7.5×10^{-12} J

D. 8.3×10^{-29} J

Question 7

Which of the following statements best describes what the Michelson–Morley experiment attempted to measure?

A. the speed of Earth through space

B. changes in the speed of Earth through space

C. accuracy obtainable with an optical interferometer

D. differences in the speed of light in different directions

Question 8

One of Einstein's postulates of special relativity was that 'the laws of physics are the same in all inertial reference frames'.

Scientists are planning an experiment that must be conducted in an inertial reference frame. They choose a location in deep space, far from the gravitational field of any star or planet.

Which of the following is the best option for them to choose?

A. a laboratory in a stationary slowly rotating spaceship

B. a laboratory in a spaceship hurtling through space at $0.99c$

C. a laboratory in a spaceship moving at $0.99c$ that is gradually slowing down

D. a laboratory in a very slowly moving spaceship that is gaining speed

Question 9

Scientists observe the path of a short-lived elementary particle in a detector. It is created in the detector and exists only for a short time, leaving a path of length 5.4 mm long. The scientists measure its speed as 2.5×10^8 m s^{-1}, giving $\gamma = 1.81$.

What is the proper lifetime of the particle?

A. 5.3×10^{-11} s

B. 3.3×10^{-11} s

C. 1.8×10^{-11} s

D. 1.2×10^{-11} s

Question 10

Which of the following statements best explains why it is impossible to accelerate particles (such as electrons) so that they are travelling at the speed of light?

A. It is directly forbidden by one of Einstein's postulates.

B. As particles increase in speed, the rest mass (m_0) tends towards an infinite value.

C. The kinetic energy of particles, given by $E_K = (\gamma - 1)m_0c^2$, tends towards an infinite value.

D. The speed of particles is given by L/t; this is equal to $L_0/t_0\gamma^2$ and this value tends towards infinity.

Question 11

Which of the following statements about proper length is the most accurate?

A. The proper length of an object is always greater than or equal to another measure of the length of the object.

B. The proper length of an object is always less than another measure of the length of the object.

C. The proper length of an object is sometimes less than another measure of the length of the object, and sometimes greater than or equal to another measure of the length of the object.

D. The proper length of an object can only be measured by an observer who is moving relative to the object.

Detailed study 1 – Einstein's special relativity

Question 1

Which of the following factors affects the speed of light?

A. the electrical properties of the medium through which light is travelling

B. the speed of the observer of the light

C. the speed of the light-emitting source

D. none of the above; the speed of light never changes

Question 2

An alarm is sounding in the centre of a large indoor basketball court. A stationary player measures the speed of sound as 335 m s^{-1}. A player runs directly towards the alarm (at 5 m s^{-1}) and another runs directly away from the alarm (also at 5 m s^{-1}). As they run they both measure the speed of sound using a small portable device. The situation is shown in Figure 1.

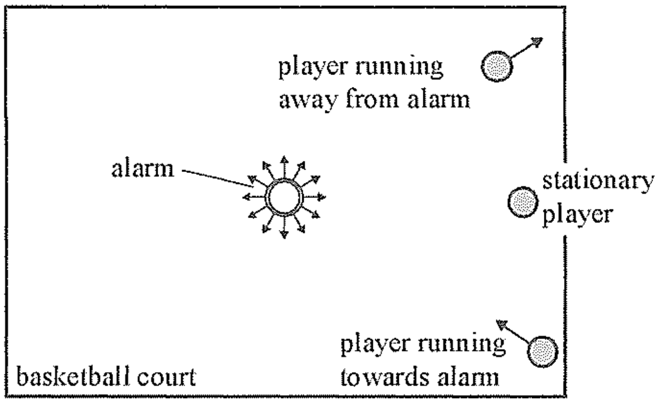

Figure 1

Which one of the following pairs of measurements is the best estimate of the speed of sound that would be measured by the running players?

	Player running away from alarm	Player running towards alarm
A.	335 m s^{-1}	335 m s^{-1}
B.	340 m s^{-1}	330 m s^{-1}
C.	325 m s^{-1}	345 m s^{-1}
D.	330 m s^{-1}	340 m s^{-1}

Question 3

A quasar, a distant star, is visible to amateur astronomers. When observed, it is at a distance of 2.5×10^{25} m from Earth and is travelling away from Earth at a speed of $0.16c$.

Which of the following is the best statement about the light from the quasar?

A. The light from the quasar will be travelling slower than 3×10^8 m s^{-1} when the light reaches Earth.

B. The light from the quasar will be travelling faster than 3×10^8 m s^{-1} when the light reaches Earth.

C. The light from the quasar has taken 2.6×10^9 years to reach Earth.

D. The light from the quasar has not yet had time to reach Earth.

Question 8

Which of the following statements about the **proper time** between two events is the most accurate?

A. It is always shorter than or equal to another measurement of the time interval between the two events.

B. It is always longer than or equal to another measurement of the time interval between the two events.

C. It may be greater than, equal to or less than another measurement of the time interval between the two events.

D. It can never be measured by an observer who is located at the same position as the two events.

Use the following information to answer Questions 9 and 10.

Spaceship A has a circular window in its side. Alan, a crew member of spaceship A, measures the diameter of the window as 20 m. Figure 2 shows spaceship A at **rest**.

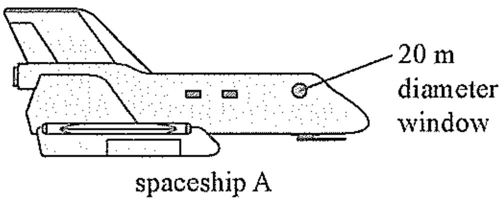

Figure 2

Briony is a crew member of spaceship B. She measures the dimensions of the window as spaceship B moves past spaceship A at a relative speed of $0.866c$ ($\gamma = 2.00$).

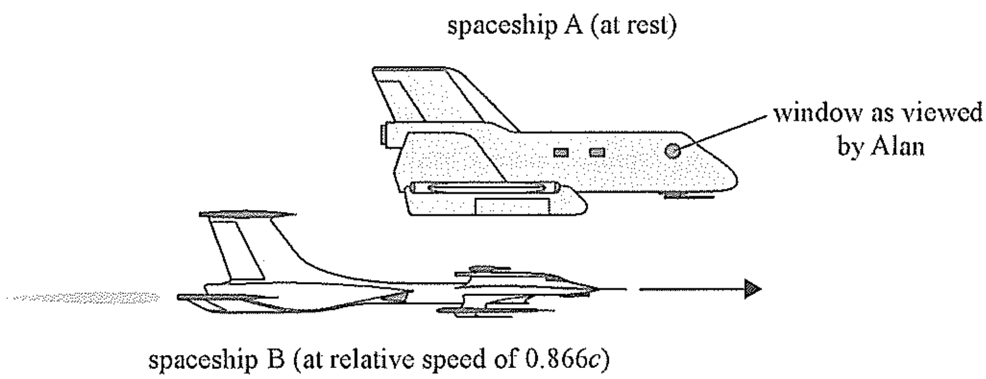

Figure 3

Question 2

Students use sound to test the ideas of the Michelson–Morley experiment. They conduct an experiment on an outdoor basketball court on a windy day.

Student A stood at the western end and created a loud pulse of sound. Student B stood 30.0 m away at the eastern end with a sound detector, as shown in Figure 1.

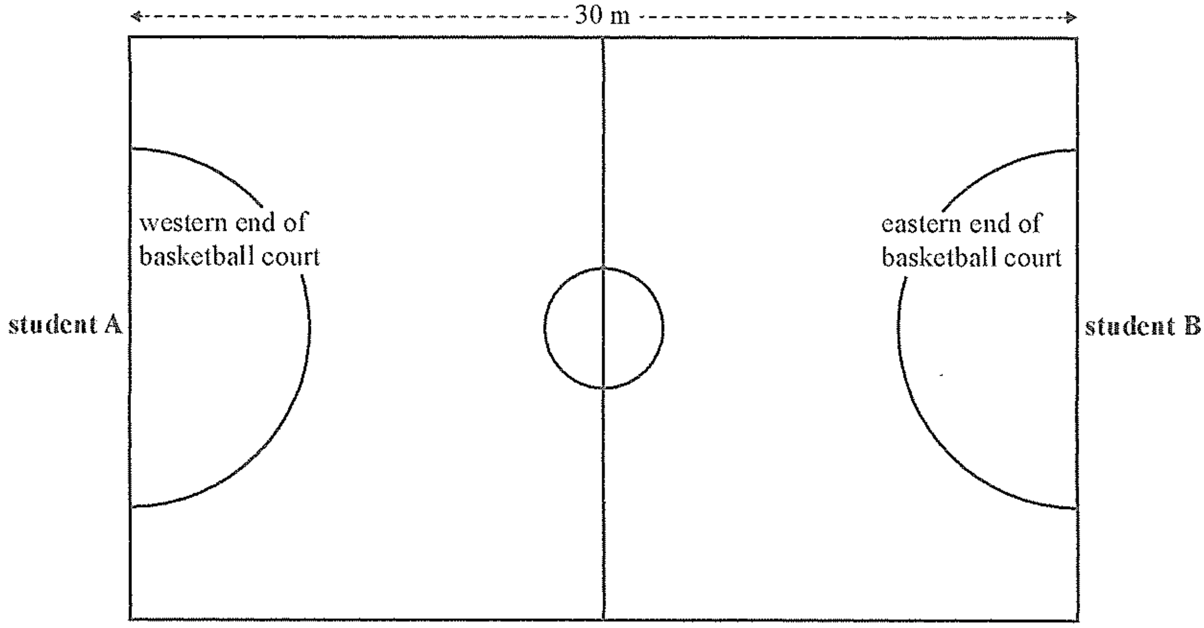

Figure 1

They found that the sound travelling towards the eastern end took 0.0857 s to reach student B.

Student B, at the eastern end, then created a loud pulse of sound. This time the sound travelling towards the western end took 0.0909 s to reach student A.

Which one of the following best explains their observations?

A. The wind was blowing to the east at 10 m s^{-1}.

B. The wind was blowing to the east at 20 m s^{-1}.

C. The wind was blowing to the west at 20 m s^{-1}.

D. The speed of sound is the same in all inertial reference frames.

Question 3

Scientists accelerate a proton from rest to a final speed where its relativistic mass is 5.1×10^{-27} kg.

The rest mass of a proton is 1.7×10^{-27} kg.

How much work was done on the proton?

A. 3.1×10^{-10} J

B. 3.1×10^{-17} J

C. 1.0×10^{-18} J

D. 3.4×10^{-27} J

Question 4

The spaceship *Andromeda* (A) is travelling at $0.7c$ towards the asteroid Ceres (C). It sends a light pulse to the nearby ship *Bradbury* (B), which is approaching the asteroid from the far side at $0.8c$, as shown in Figure 2.

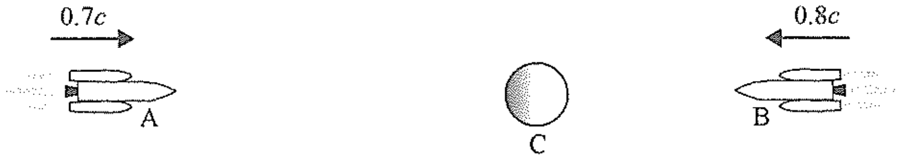

Figure 2

The speed of the light pulse as measured from each body is

A. greatest for A and least for B.
B. greatest for B and least for A.
C. greatest for C and least for B.
D. the same for each body.

Question 5

A physicist purchased a limousine, but found that it was twice as long as her garage. She reasoned that in the garage's reference frame, it should be possible for a moving limousine to fit exactly inside the garage for an instant.

What is the minimum speed at which the limousine would have to travel in order for this to work?

A. $\frac{c}{\sqrt{2}}$

B. $\frac{3}{4}c$

C. $\frac{\sqrt{3}}{2}c$

D. $\sqrt{3}c$

Question 6

A neutral pion is a type of particle. In a collider experiment, a neutral pion with $\gamma = 10.0$ decays into two photons. The total energy of both photons together is measured to be 2.17×10^{-10} J. Before the decay, only the neutral pion exists; after the decay, only the photons exist.

What is the rest mass of the neutral pion?

A. 2.41×10^{-28} kg
B. 2.41×10^{-27} kg
C. 7.23×10^{-27} kg
D. 7.23×10^{-20} kg

Question 7

It is not possible for a particle with a rest mass greater than zero to be accelerated to a speed of c.

Which one of the following is the best explanation for this?

A. It would violate causality and is therefore impossible.

B. As v approaches c, the rest mass of the particle approaches infinity.

C. Massless particles such as photons are constrained to travel at a speed of c.

D. An infinite amount of work would be required in order to accelerate the particle to a speed of c.

Question 8

Which one of the following statements is correct?

A. Proper time cannot be measured on a moving clock.

B. Proper time is the time interval between two events that is measured by a stationary clock.

C. Proper time is the shortest possible time interval between two events that any observer can measure.

D. An observer who measures a proper time is the only observer performing a correct measurement of the time between two events.

Question 9

Lucy is on a train travelling at $0.8c$. The train passes Edmund, who is standing on the platform at a train station.

They each measure a different length for the train and also measure a different length for the platform.

Which one of the following statements is correct?

A. Lucy measures a proper length for the train because she is stationary with respect to the train.

B. Edmund measures a proper length for the train because he is stationary in his reference frame.

C. Edmund measures a proper length for both the platform and the train because he is standing still.

D. Lucy measures a proper length for the platform because she passes the start and the end of the platform over the course of her journey.

Use the following information to answer Questions 10 and 11.

The global positioning system (GPS) makes use of satellites in orbit around Earth. The student shown in Figure 3 is standing on the ground while one such satellite passes directly overhead.

The satellite has $\gamma = (1 + [5 \times 10^{-11}])$.

Approximate the satellite's path as a horizontal straight line and neglect Earth's gravitational field. Assume that both the satellite and the student are in inertial reference frames.

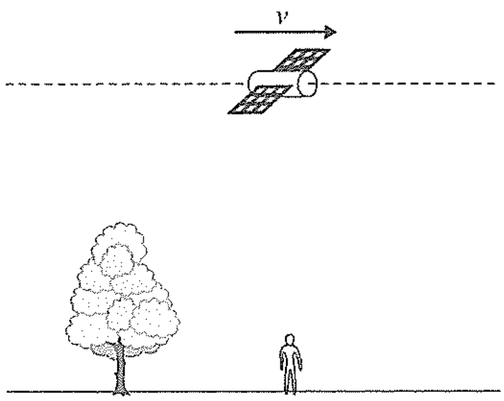

Figure 3
not to scale

Question 10

If exactly 1 s passes as measured on the satellite, how much time elapses for the student?

A. $(1 - [5 \times 10^{-11}]) \times 1$ s

B. $(1 + [5 \times 10^{-11}]) \times 1$ s

C. $\left(\frac{1}{1+[5\times10^{-11}]}\right) \times 1$ s

D. 1 s exactly

Question 11

It is necessary to have accurate measurements of distances. In the student's reference frame, a satellite that is vertically overhead is measured to be 20 000 km distant from the student.

What measurement would instruments on the satellite take of the same distance?

A. $(1 - [5 \times 10^{-11}]) \times 20\,000$ km

B. $\left(\frac{1}{1+[5\times10^{-11}]}\right) \times 20\,000$ km

C. 20 000 km

D. $(1 + [5 \times 10^{-11}]) \times 20\,000$ km

End of Detailed study 1

SECTION B

Instructions for Section B

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Detailed study 1 – Einstein's special relativity

Question 1

The concept of an 'inertial frame' is widely used in physics.

Which one of the following statements best describes an inertial frame?

A. a frame in which relativistic effects do not occur

B. a frame in which Newton's first law of physics is always obeyed

C. a frame in which all time measurements result in proper time

D. a frame whose acceleration is small compared to g

Question 2

A number of experiments have played a part in the history of the theory of relativity.

Which one of the following is true about the Michelson–Morley experiment?

A. More accurate versions of this experiment produced results that were significantly different from the original results.

B. It was only ever interpreted as confirming Einstein's postulate regarding the speed of light.

C. It was designed to prove Einstein's postulate regarding the speed of light.

D. It did not detect a difference between the speed of light in directions parallel to Earth's motion through space and in directions perpendicular to that motion.

Question 3

A person moving parallel to the length of a 2.00 m ruler observes the change of length of this ruler due to relativity to be 0.010 m.

What is the person's speed relative to the ruler?

A. $0.0050c$

B. $0.010c$

C. $0.10c$

D. $0.90c$

Use the following information to answer Questions 4–6.

Two spacecraft travel in opposite directions, with spacecraft *Ajax* travelling at a speed of 0.5c and spacecraft *Hector* travelling at a speed of 0.4c. Both are travelling relative to the inertial frame of the galaxy. The situation is shown in Figure 1.

Figure 1

A radio signal is emitted by *Ajax* towards *Hector*. The navigator of *Hector* uses the classical physics understanding of radio waves travelling at a speed relative to a medium fixed with respect to the galaxy.

Question 4

Using this classical understanding, the speed of the radio signal relative to *Hector* is expected to be

A. c

B. 0.6c

C. 0.5c

D. 0.1c

Question 5

Measured in the frame of *Ajax*, the radio signal reaches *Hector* 0.0100 s after it is emitted by *Ajax*.

According to the navigator of *Ajax*, who is correctly using special relativity, how far did the radio signal travel between leaving *Ajax* and reaching *Hector*?

A. 3000 km

B. 300 km

C. 4200 km

D. 1500 km

Question 6

How can proper time be measured for the interval between the radio signal being emitted on *Ajax* and the signal reaching *Hector*?

A. Use measurements made by the crew on *Ajax*.

B. Use measurements made by the crew on *Hector*.

C. Use measurements made by an observer stationary at the point where the signal was emitted.

D. No single observer can measure proper time for this case.

Use the following information to answer Questions 7–9.

An astronaut takes a clock in her spacecraft and measures the clock's period while the spacecraft is stationary in the inertial frame of our galaxy. She then measures its period when the spacecraft is moving at a constant velocity of $0.60c$, relative to the galaxy's frame.

Question 7

The period of the clock as measured in the **moving** spacecraft

A. is smaller than when the spacecraft was stationary in our galaxy's inertial frame.

B. is the same as when the spacecraft was stationary in our galaxy's inertial frame.

C. is greater than when the spacecraft was stationary in our galaxy's inertial frame.

D. depends on the particular details of the clock mechanism.

The clock was built using two mirrors between which a pulse of light is repeatedly reflected, as shown in Figure 2. The proper length between the two mirrors is 5.00 m. The spacecraft's velocity ($0.60c$ relative to our galaxy; $\gamma = 1.25$) is in the direction AB.

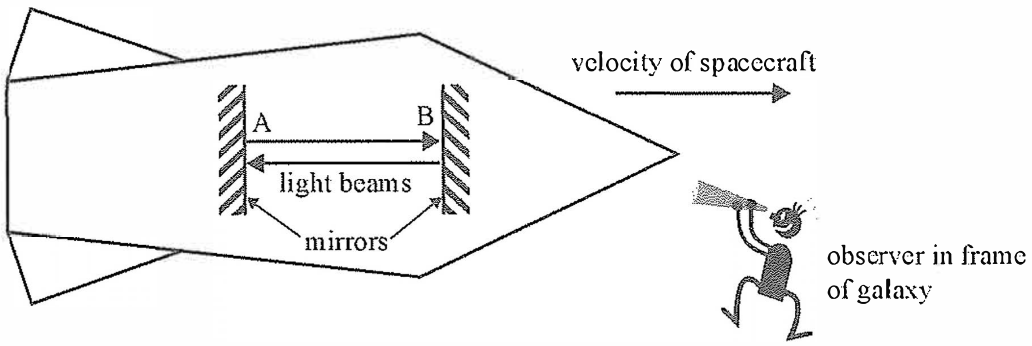

Figure 2

Question 8

According to an observer in the frame of our galaxy, the distance between the mirrors is closest to

A. 7.25 m

B. 5.00 m

C. 4.00 m

D. 3.00 m

Question 9

One period of this clock is the time taken for light to travel from A to B and back to A.

According to an observer in the frame of our galaxy, the period of this clock is closest to

A. 42 ns

B. 27 ns

C. 21 ns

D. 13 ns

Use the following information to answer Questions 10 and 11.

A pion and its antiparticle, each at rest, annihilate to produce two photons whose total energy is 4.5×10^{-11} J. Apart from the two photons, nothing else is produced in this process. The masses of a pion and its antiparticle are the same.

Question 10

The rest mass of the pion is

A. 1.3×10^{-28} kg

B. 2.5×10^{-28} kg

C. 5.0×10^{-28} kg

D. 7.5×10^{-20} kg

Question 11

The pion is now accelerated from rest before colliding with its antiparticle.

What work must be done on one pion so that it has γ equal to 3.00?

A. 4.5×10^{-11} J

B. 2.2×10^{-11} J

C. 1.1×10^{-11} J

D. 9.0×10^{-11} J

SECTION B

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Detailed study 1 – Einstein's special relativity

Question 1

One key postulate of Einstein's special theory of relativity can be described as

A. $E = mc^2$.

B. nothing can travel faster than the speed of light.

C. the laws of physics are the same in all inertial (non-accelerated) frames of reference.

D. all inertial observers obtain the same result when measuring the time and position of an event.

Question 2

The following statements reflect views held before Einstein proposed the special theory of relativity.

Which one of these views is now still considered to be true?

A. The observed speed of light in a medium depends on the speed of an observer relative to that medium.

B. The speed of light in a region depends only on the values of electric and magnetic properties of that region.

C. Light is a wave comprising oscillating electric and magnetic fields that cannot travel through empty space.

D. The inertial frame of a medium in which light is travelling is a special frame and, in that frame, the speed of light is c.

Question 3

A star moving directly away from Earth at speed v emits light at a particular wavelength. This light is measured on Earth and the wavelength is found to have increased.

Which one of the following is true?

A. The speed of the light leaving the star is $c - v$, causing the frequency of the light source to decrease.

B. The speed of the light received by the observer on Earth is $c - v$, causing the observed wavelength to increase.

C. The observed change of wavelength is not due to a change in the speed of light, but relative motion of the source and observer.

D. The observed change of wavelength is due to length contraction resulting from the relative movement of the star with respect to Earth.

Question 10

A particle of rest mass m_0 is accelerated from rest to $0.6c$ relative to Earth's frame.

Which one of the following statements is true?

A. In its own frame, the mass of the particle is now $1.25m_0$.

B. The work done to accelerate the particle is equal to the kinetic energy of the particle.

C. The kinetic energy of the particle in Earth's frame is $\frac{1}{2}m_0(0.6c)^2$.

D. The increase in total energy of the particle (measured in Earth's frame) is due to an increase in both the kinetic energy of the particle and the rest energy of the particle.

Question 11

According to Einstein's relativity theory, the rest energy is m_0c^2 for a particle of rest mass m_0 and the kinetic energy of the particle is $(\gamma - 1)\, m_0c^2$, where $\gamma = \dfrac{1}{\sqrt{1-\dfrac{v^2}{c^2}}}$.

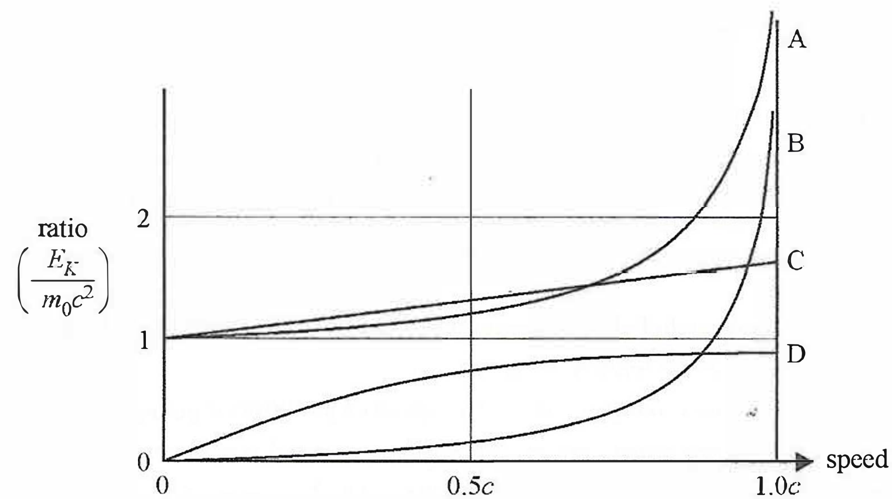

Figure 3

Which one of the curves in Figure 3 best gives the relationship of kinetic energy to rest energy $\left(\dfrac{E_K}{\text{rest energy}}\right)$ as a function of speed v?

A. curve A

B. curve B

C. curve C

D. curve D

SECTION B

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Unless otherwise indicated, the diagrams in this book are **not** drawn to scale.

Detailed study 1 – Einstein's special relativity

Use the following information to answer Questions 1 and 2.

Anna and Barry have identical quartz clocks that use the precise period of vibration of quartz crystals to determine time. Barry and his clock are on Earth. Anna accompanies her clock on a rocket travelling at constant high velocity, *v*, past Earth and towards a space lab (which is stationary relative to Earth), as shown in Figure 1.

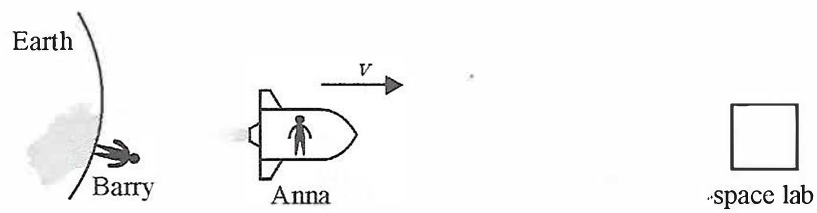

Figure 1

Question 1

Which one of the following statements correctly describes the behaviour of these two clocks?

A. The period of vibration in Anna's clock (as observed by Anna) will be shorter than the period of vibration in Barry's clock (as observed by Barry).

B. The period of vibration in Anna's clock (as observed by Anna) will be longer than the period of vibration in Barry's clock (as observed by Barry).

C. The period of vibration in Anna's clock (as observed by Anna) will be the same as the period of vibration in Barry's clock (as observed by Barry).

D. Only the time on Barry's clock is reliable because it is in a frame that is not moving.

Question 2

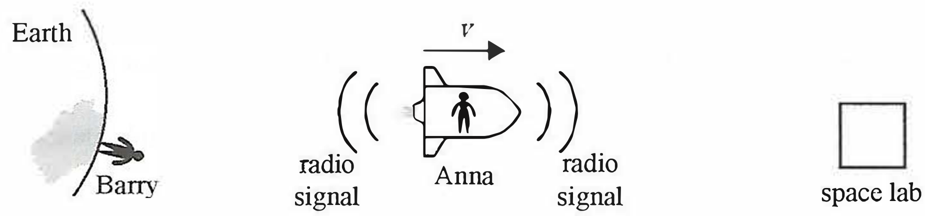

Figure 2

When Anna is halfway between Earth and the space lab, she sends a radio pulse towards Earth and towards the space lab, as shown in Figure 2.

As observed by Anna, which one of the following statements correctly gives the order in which this signal is received by Barry and by the space lab?

A. Barry receives the signal first.

B. The space lab receives the signal first.

C. The signal is received by Barry and the space lab at the same time.

D. It is not possible to predict since special relativity applies to light but not to radio signals.

Question 3

Figure 3 shows Carla moving towards a loudspeaker at a speed of v_C and Han running towards a light source at speed v_H.

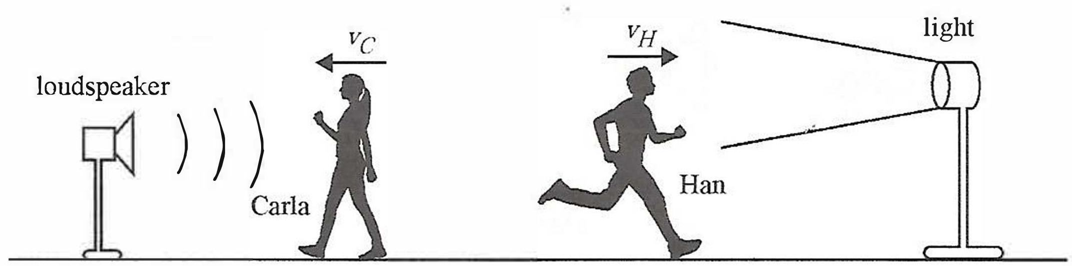

Figure 3

Which of the following correctly shows the speed of sound relative to Carla and the speed of light relative to Han? (The speed of sound in air is v_S.)

	Speed of sound relative to Carla	Speed of light relative to Han
A.	v_S	c
B.	$v_S + v_C$	$c + v_H$
C.	$v_S + v_C$	c
D.	$v_S - v_C$	$c - v_H$

Question 7

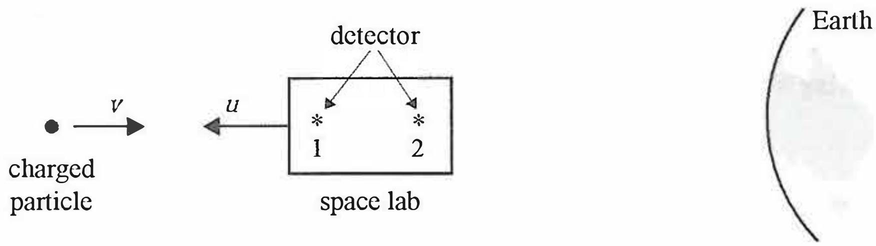

Figure 4

A space lab travelling at $u = 0.8c$ ($\gamma = 1.67$) away from Earth can record high-energy charged particles passing through its detectors. One particle is travelling towards Earth at $v = 0.91c$ ($\gamma = 2.4$) **relative to the space lab**.

Two detectors, numbered 1 and 2 in Figure 4, are 2.0 m apart in the space lab's frame.

How far apart are the two detectors in this particular particle's frame?

A. 0.83 m

B. 1.2 m

C. 3.3 m

D. 4.8 m

Question 8

A linear accelerator is used to increase the speed of a charged particle from rest. The particle is accelerated between two electrodes in a time of 40 ns. The particle reaches a speed at which $\gamma = 1.6$

What is the time taken for this acceleration in the particle's own frame of reference?

A. 40 ns

B. 40 ns divided by the mean value of γ during the trip between the two electrodes

C. 64 ns

D. cannot be determined using special relativity as it does not apply to accelerated frames of reference

Question 9

When a proton is accelerated from rest, it gains a kinetic energy of 1.20×10^{-10} J.

What value of γ is reached? (The rest mass of a proton is 1.67×10^{-27} kg.)

A. 2.2

B. 1.8

C. 1.5

D. 1.3

Question 10

A high-energy proton with $\gamma = 3$ collides with a stationary nucleus and rebounds in the opposite direction to its original motion. The kinetic energy of the proton after the collision is m_0c^2, where m_0 is the rest mass of a proton. The nucleus gains kinetic energy and there is no other change to the energy of the nucleus.

Which one of the following is the kinetic energy of the nucleus after the collision?

A. $0.5\ m_0c^2$

B. $1.0\ m_0c^2$

C. $1.5\ m_0c^2$

D. $2.5\ m_0c^2$

Question 11

Which statement best describes the speed of light in various media, including a vacuum?

A. The speed of light in a material will vary if the material is moved at a high speed relative to a light source.

B. The speed of light in a material depends only on the amount of length contraction of the material.

C. The speed of light in a medium depends only on the electrical and magnetic properties of the medium.

D. The speed of light in a medium depends directly on the mass density of the material.