2004

Question 10 (2 marks, 59%)

The electron accelerator at Stanford University is 3.2 km long. Electrons reach a velocity of 0.9999995 c, which means the Lorentz factor is 1000.
As measured by a scientist at the accelerator laboratory, how long would the electron take to travel the length of the accelerator?

time = distance/speed $t = \frac{s}{v} = \frac{3.2\times10^3}{3\times10^8} = 1.1\times10^{-5}s$

Question 11 (3 marks, 44%)
How long would the electron measure its time of travel to be?

Time found in question 10 is dilated time. Time in the electron's frame of reference is a proper time $t_0 = \frac{t}{\gamma} = 1.1\times10^{-8}s$

2005

Question 5 (3 marks, 48%)

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.

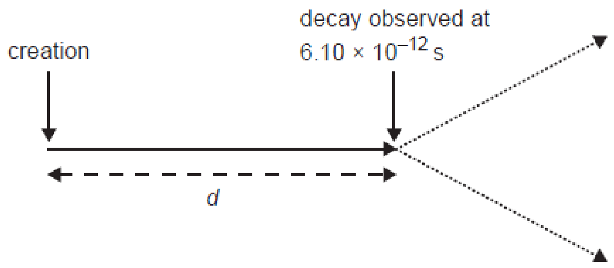


Figure 3

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

Time measured by the scientists is dilated time. Time measured in meson's frame of reference is a proper time. $t_0 = \frac{t}{\gamma} = 3.05\times10^{-13}s$

Question 7 (3 marks, 27%)

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.

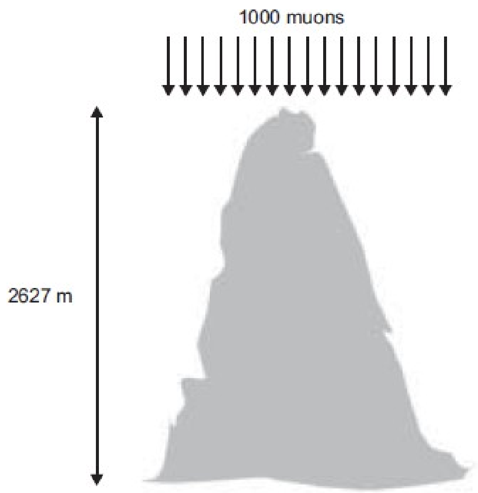


Figure 4

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

$$\gamma = \frac{1}{\sqrt{1-(\frac{v}{c})^2}} = 10.01$$

Time measured by experimenters is dilated time. Time in the muons frame of reference is a proper time. So $t = t_0\gamma = 2.2 \times 10 = 22\ \mu s$

2007

Question 4 (2 marks, 58%)
A spacecraft is approaching Earth at a speed of 0.1000 c. When the pilot measures the distance to the control tower to be 90 000 km, a signal is sent to inform the control tower of the spacecraft's approach. The speed of light can be taken as 3.000 × 10^8 m/ s. What is the value of the Lorentz factor for the approaching spacecraft?

$$\gamma = \frac{1}{\sqrt{1-(\frac{v}{c})^2}} = \frac{1}{\sqrt{1-0.1^2}} = 1.005$$

Question 7 (45%)

The Global Positioning System (GPS) is commonly used to locate positions on Earth. A highly accurate clock on board each orbiting satellite continually broadcasts the time to GPS receivers on Earth. Each GPS receiver has a clock that is assumed to be **identical** to that on the satellite. Over a period of exactly 24 hours the total time difference between the clock in the orbiting satellite and the clock in the GPS receiver is not zero, but 0.000038 s.
Assuming this time difference is due to special relativity, which **one or more** of the following statements is correct?
A. The GPS receiver measures the satellite clock running at the same rate as itself.
B. The GPS receiver measures the satellite clock running more slowly than itself.
C. The GPS receiver measures the satellite clock running faster than itself.
D. The orbit radius of the satellite is shortened due to relativity.

Since the clock in the satellite is moving relative to the ground-based observer, the satellite clock will appear to be running slowly. The correct option was B.

Question 8 (55%)

One of the several subatomic particles produced in a historic experiment at the SACLAY research laboratory in France was a pi-minus (or pion). The pion had a very high speed, v, corresponding to a **Lorentz factor of 16**. From the data, the experimenters determined that the pion existed for 4.16 × 10^–7 s before decaying into two other particles.
Which of the options **(A–D)** below is the best estimate of how long the pion existed, as measured in its own frame of reference?
A. 2.60 × 10^–8 s
B. 1.04 × 10–^7 s
C. 4.16 × 10–^7 s
D. 6.65 × 10–^6 s
The experimenters measure the lifetime to be longer than the proper time. So, to obtain the proper time the experimenters' time must be divided by 16, giving option A.
Question 9 (3 marks, 47%)

From the known Lorentz factor, show that the average speed of the pion was 0.998 c.

$$\gamma = \frac{1}{\sqrt{1-(\frac{v}{c})^2}} \quad 1-(\frac{v}{c})^2 = \frac{1}{\gamma^2} \quad (\frac{v}{c})^2 = 1-\frac{1}{16^2} \quad \frac{v}{c} = \sqrt{1-\frac{1}{16^2}} = 0.998$$

2008

Question 2 (59%)

For which of the following values of the Lorentz factor, γ, would relativistic changes in time, length and mass **not** be observed?

A. close to 0
B. significantly less than 1
C. approximately equal to 1
D. significantly greater than 1

ANS: C

Question 11 (67%)

An electron with a Lorentz factor of 4 travels in a straight line a distance of 600 m as measured in the laboratory frame of reference.
Which one of the following best gives the speed of the electron?

A. 0.25 c
B. 0.94 c
C. 0.97 c
D. 0.99 c

ANS: C

2009

Question 9 (83%)

An experiment is set up in an accelerator laboratory to study muons. A muon is an elementary particle. The muons are moving at a speed of 0.95 *c* (γ= 3.2). However, a particular muon only exists for a period of time of 4.8 × 10^–6 s (as measured by the experimenters). After this time the muon decays into other particles.
Which one of the following best gives the lifetime of the muon as measured in its own frame of reference?

A. 4.7 × 10^–7 s
B. 1.2 × 10^–6 s
C. 1.5 × 10^–6 s
D. 4.6 × 10^–6 s

C *Time measured in muon's own frame of reference is its proper time***.**

2010
Question 7 (54%)

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.

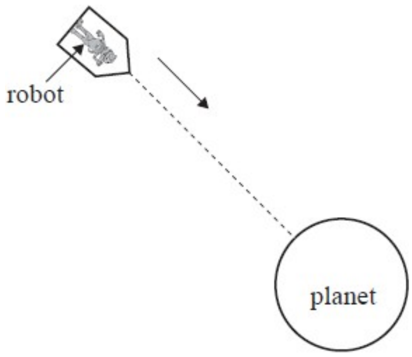


Figure 3

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

The robot measures the proper time
Ans:A

Question 8 (31%)

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.

Ans: D *Proper time is measured by a clock and is the time between two events that occur at the same place as the clock.*

2011

Question 9 (42%)

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, giving γ = 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

Time measured by scientists is $t = \frac{d}{v} = \frac{5.4\times10^{-3}}{2.5\times10^{8}} = 2.16\times10^{-11} s$ *and this is dilated time. Time in the particle frame of reference is a proper time.* $t_0 = \frac{t}{\gamma} = \frac{2.16\times10^{-11}}{1.81} = 1.2\times10^{-11}$ **ANS: D**

2012

Question 7 (64%)

A particle is travelling at a speed of 1.4 × 10^8 m/ s.

If its speed is doubled to 2.8 × 10^8 m s–1, which of the following is the best estimate of the ratio

$$\frac{\text{value of } \gamma \text{ at the higher speed}}{\text{value of } \gamma \text{ at the lower speed}} ?$$

A. 1.4
B. 2.0
C. 2.5
D. 3.0

$$\frac{\sqrt{1-(\frac{1.4}{3})^2}}{\sqrt{1-(\frac{2.8}{3})^2}} = 2.4$$

ANS: C

2013

Question 8 (24%)

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.

ANS: C

Question 10 (50%)

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 γ = (1 + [5 × 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.

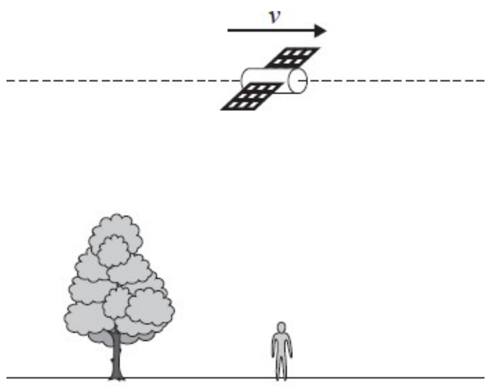


Figure 3
not to scale

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

Time measured on the satellite is the proper time. Student measures dilated time
$t = t_0 \times \gamma$
ANS: B

2014

Question 6 (37%)

Two spacecraft travel in opposite directions, with spacecraft *Ajax* travelling at a speed of 0.5*c* and spacecraft *Hector* travelling at a speed of 0.4*c*. 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.
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.

To measure proper time the two events need to occur at the same place relative to the observer, and thus can be timed with a single clock located at that place. This is not the case, hence option ***D*** *was the correct answer.*

2015

Spacecraft *S66* is travelling at high speed away from Earth carrying a highly accurate atomic clock. Another spacecraft, *T50*, is travelling in the opposite direction to *S66*, as shown in Figure 1.

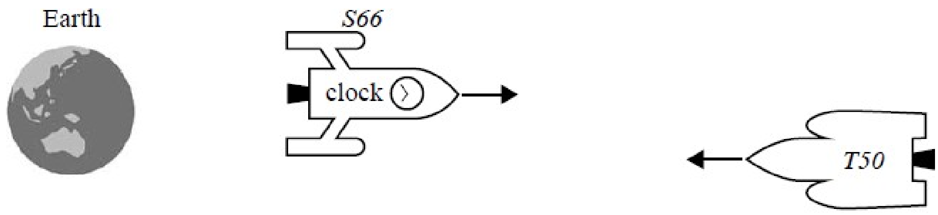


Figure 1

Question 4 (71%)
Which one of the following observers will be able to measure proper time using this clock?
A. an astronaut seated on spacecraft *S66* five metres behind the clock's position
B. a scientist on Earth at the clock's original position
C. no observer can measure proper time since light within the clock moves at the speed of light
D. the navigator of the other spacecraft, *T50*, travelling at the moment when that navigator is opposite the clock

ANS: A
Question 5 (52%)
An observer, *E*, on Earth emits a short radio pulse to spacecraft *S66*, which reflects it directly back towards the observer. The time elapsed for *E* between sending and receiving the pulse is 20.0 ms.
A. According to *E*, spacecraft *S66* was more than 3000 km away when the pulse reached it.
B. According to *E*, the pulse took longer to reach spacecraft *S66* than it did to return from spacecraft *S66* to *E*.
C. The 20.0 ms interval measured by *E* is not a proper time because the radio pulse travelled away and back.
D. According to spacecraft *S66*, the time interval between the signal being sent and being received back by *E* is greater than 20.0 ms.

ANS: D
Question 6 (61%)
The clock on spacecraft *S66* has an indicator showing time intervals of 0.100 s. The navigator of spacecraft *T50* observes that the duration of those time intervals is 0.115 s. What is the relative speed of spacecraft *S66* to spacecraft *T50*?

A. 0.80c
B. 0.70c
C. 0.60c
D. 0.50c
ANS: D

$$\gamma = \frac{0.115}{0.1} = 1.15 \quad \frac{v}{c} = \sqrt{1 - \frac{1}{1.15^2}} = 0.5$$

2016

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.

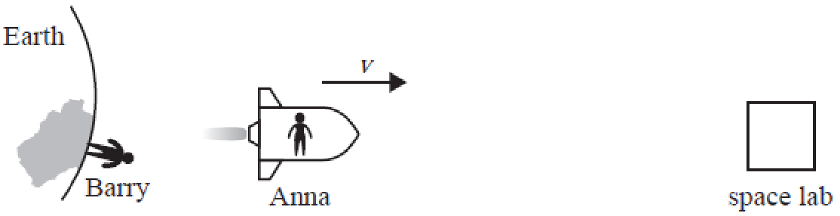


Figure 1

Question 1 (48%)

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.

ANS: C *Although both observers are in different inertial frames each will observe time passing at the same rate in their own frames.*

Question 2 (45%)

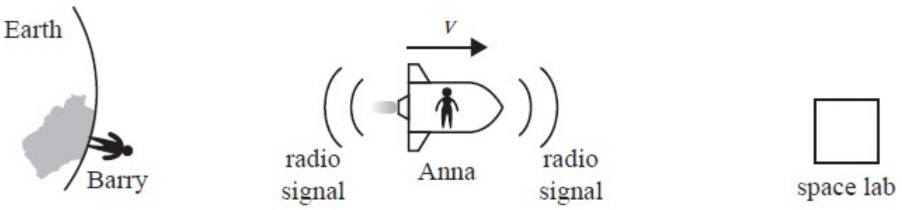


Figure 2

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.

ANS: B *Anna sends the two pulses simultaneously from her perspective and both pulses travel at the same speed. The space lab is moving towards her while Barry moves away, so she will see the signal reach the spacelab first as it will travel a shorter distance.*

Use the following information to answer Questions 5 and 6.
Pions are particles that are present in cosmic rays striking Earth. Pions decay, with a half-life of 26 ns. The half-life is the time taken for half of a large number of pions to decay.

Question 5 (69%)
In which frame of reference will the undilated value of the half-life be correctly observed?
A. in the frame of the high-energy source of each pion
B. in each pion's own frame
C. in any inertial frame
D. in Earth's frame

ANS: B

Question 6 (71%)

Consider one pion approaching Earth at a speed of 0.98*c*. It decays 26 ns in its own frame of reference after it is formed.
How long did the pion exist as observed in Earth's frame of reference?
A. 5.2 ns
B. 26 ns
C. 130 ns
D. 650 ns

ANS: C $\boldsymbol{\gamma = \frac{1}{\sqrt{1-0.98^2}} = 5 \;\; t = 26 \times 5 = 130}$

2017

Question 11
Tests of relativistic time dilation have been made by observing the decay of short-lived particles. A muon, travelling from the edge of the atmosphere to the surface of Earth, is an example of such a particle.
To model this in the laboratory, another elementary particle with a shorter half-life is produced in a particle accelerator. It is travelling at 0.99875*c* ($\gamma = 20$). Scientists observe that this particle travels 9.14×10^{-5}m in a straight line from the point where it is made to the point where it decays into other particles. It is not accelerating.

a. 42% (2 marks)
Calculate the lifetime of the particle in the scientists' frame of reference.

As scientist is stationary relative to the accelerator time is just distance over speed.

$$t = \frac{d}{v} = \frac{9.14 \times 10^{-5}}{0.99875 \times 3 \times 10^{8}} = 3.05 \times 10^{-13} s$$

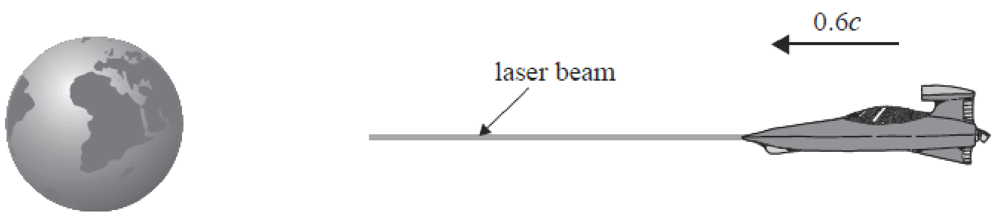
c. 8% (3 marks)
Explain why the scientists would observe more particles at the end of the laboratory measuring range than classical physics would expect.

Due to the particle's velocity, its half-life as measured in the scientists' frame of reference is increased. Therefore, fewer particles will decay before reaching the detector and more particles will be detected.

2018 NHT

Question 11 M/C

An alien spaceship has entered our solar system and is heading directly towards Earth at a speed of 0.6*c*, as shown in the diagram below. When it reaches a distance of $3.0 \times 10^{11} m$ from Earth (in Earth's frame of reference), the aliens transmit a 'be there soon' signal via a laser beam.



How long will it take for the signal to reach Earth according to an observer on Earth?
A. 1.0 s
B. 1.7 s
C. 625 s
D. 1000 s

As observer is stationary relative to the Earth time is just distance over speed.

$t = \frac{d}{v} = \frac{3.0 \times 10^{11}}{3 \times 10^{8}} = 1000 s$ **ANS: D**

Question 14 (3 marks)

An Earth-like planet has been discovered orbiting a distant star. A hypothetical mission to this planet is suggested. The planet is $1.0 \times 10^{18} m$ from Earth. The spaceship suggested for the mission can travel at an average speed of 0.99c. Take $\gamma = 7.1$ for this speed. Scientists are concerned about the length of time the passengers would have to spend on the spaceship to travel to this planet.
Use principles of special relativity to estimate this time, in years, as measured on the spaceship.

In Earth's frame of reference time is just distance over speed.

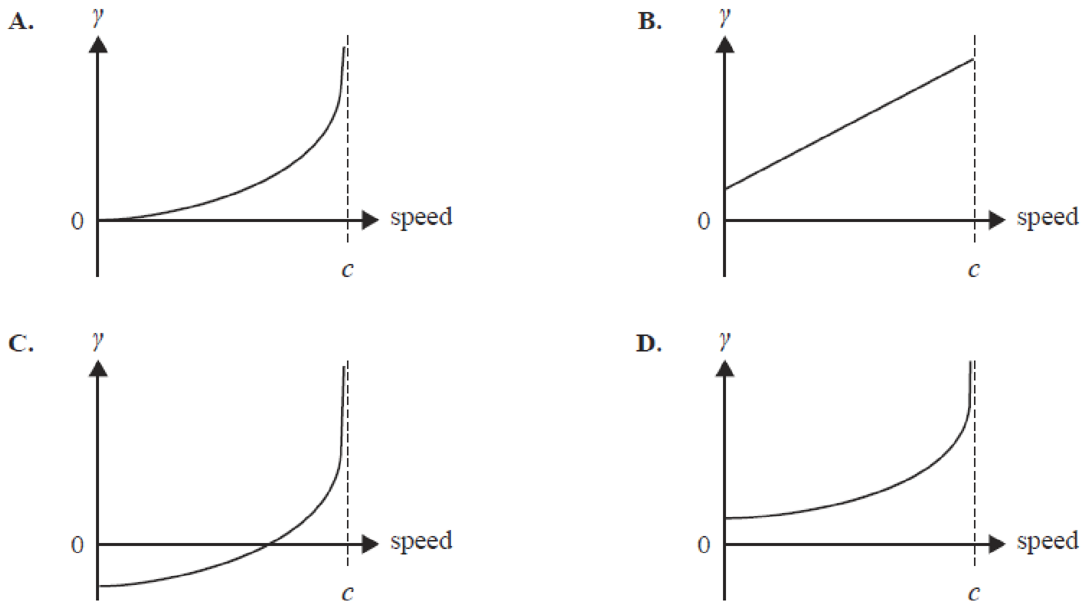
$$t = \frac{d}{v} = \frac{1.0\ \times 10^{18}}{0.99 \times 3 \times 10^{8}} = 3.367 \times 10^{9} s = 106.8\ years$$

This time is dilated from the passengers frame of reference. Their time is the proper time so $t_0 = \frac{t}{\gamma} = \frac{106.8}{7.1} = 15\ years$

2018

Question 13 M/C 58%

Which one of the following diagrams best represents the graph of γ (the Lorentz factor) versus speed for an electron that is accelerated from rest to near the speed of light, c?



ANS: D

When v=0, γ=1, so A and C out, γ is non-linear approaching infinity when v approaching c, so answer D.

Question 16 (2 marks) **(53%)**
Quasars are among the most distant and brightest objects in the universe. One quasar (3C446) has a brightness that changes rapidly with time.
Scientists observe the quasar's brightness over a 20-hour time interval in Earth's frame of reference. The quasar is moving away from Earth at a speed of 0.704c (γ = 1.41).
Calculate the time interval that would be observed in the quasar's frame of reference. Show your working.

Time measured by scientists is dilated time so for quasar

$$t_0 = \frac{t}{\gamma} = \frac{20}{1.41} = 14.2\ hours$$

2019 NHT

Question 16 M/C
In a particle accelerator, magnesium ions are accelerated to 20.0% of the speed of light. Which one of the following is closest to the Lorentz factor, γ, for the magnesium ions at this speed?
A. 1.02
B. 1.12
C. 1.20
D. 2.24

$\gamma = \frac{1}{\sqrt{1-0.2^2}} = 1.02$ **ANS: A**

Question 17 M/C
The lifetime of stationary muons is measured in a laboratory to be 2.2μs. The lifetime of relativistic muons produced in Earth's upper atmosphere, as measured by ground-based scientists, is 16 μs.
The resulting time dilation observed by the scientists gives a Lorentz factor, γ, of
A. 0.14
B. 1.4
C. 3.5
D. 7.3

$\gamma = \frac{16}{2.2} = 7.3$ **ANS: D**

Question 17 (3 marks)
A spaceship is travelling from Earth to the star system Epsilon Eridani, which is located 10.5 light-years from Earth as measured by Earth-based instruments.
If the spaceship travels at 0.85c (γ = 1.90), determine the duration of the flight as measured by the astronauts on the spaceship travelling to Epsilon Eridani. Take one light-year to be 9.46 × $10^{15} m$. Show your working.

Time in Earth's frame of reference $t = \frac{10.5}{0.85} = 12.35\ years$ *This is dilated time.*
In spaceship frame of reference $t_0 = \frac{12.35}{1.9} = 6.5\ years$

Question 11 (4 marks)

An astronaut has left Earth and is travelling on a spaceship at 0.800*c* ($\gamma = 1.67$) directly towards the star known as Sirius, which is located 8.61 light-years away from Earth, as measured by observers on Earth.

a. How long will the trip take according to a clock that the astronaut is carrying on his spaceship? Show your working.

2 marks

Time measured by observer on Earth $t = \frac{d}{v} = \frac{8.61}{0.8} = 10.76$ years 21%

Time measured by astronaut is proper time in his frame of reference $t_0 = \frac{t}{\gamma} = \frac{10.76}{1.67} = 6.44$ y

6.44 years

b. Is the trip time measured by the astronaut in **part a.** a proper time? Explain your reasoning.

2 marks 24%

Yes, proper time.

Clock is stationary in his frame of reference.