Mark schemes

1

(i) $v\left(= \frac{45}{152 \times 10^{-9}}\right) = 2.96 \times 10^8$ m s^{-1} **(1)**

2

(ii) $t = 152$ ns **(1)**

$t_0 \left[= 152\left(1 - \frac{v^2}{c^2}\right)^{1/2}\right] = 152\left(1 - \left(\frac{2.96}{3.00}\right)^2\right)^{1/2}$ **(1)**

= 25 ns **(1)**

2

QWC 2

[4]

2

(i) time taken $\left(\frac{distance}{speed} = \frac{34}{0.95 \times 3.0 \times 10^8}\right) = 1.1(9) \times 10^7$ s **(1)**

(ii) use of $t = \frac{t_0}{(1 - v^2/c^2)^{1/2}}$ where t_0 = 18 ns

and t is the half-life in the detectors' frame of reference **(1)**

$\therefore\ t = \frac{18 \times 10^{-9}}{(1 - 0.95^2)^{1/2}} = 57(.6) \times 10^{-9}$ s (1)

time taken for π meson to pass from one detector to the other
= 2 half-lives (approx) (in the detectors' frame of reference) **(1)**
2 half-lives correspond to a reduction to 25%,
so 75% of the π mesons passing the first detector
do not reach the second detector **(1)**

alternatives for first 3 marks in (ii)

1. use of $t = \frac{t_0}{\sqrt{(1 - v^2/c^2}}$, where t_0 = 18 ns

$= \frac{18}{(1 - 0.95^2)^{1/2}}$ = 57.6(ns)

journey time in detector frame (= $2t$) = 2 × 57.6ns (≈ 2 half-lives)

2. use of $t = \frac{t_0}{\sqrt{(1 - v^2/c^2}}$ where t = 119 ns

= journey time in detector frame

$t_0 = 119\sqrt{1 - 0.95^2}$ =37ns

journey time in rest frame = 2 × 18 ns (2 half-lives)

[5]

3 (a) c is the same, regardless of the speed of the light source or the observer **(1)**

1

(b) distance between detectors in rest frame of particles

(= 25 × $(1 - 0.98^2)^{1/2}$) = 5.0 m **(1)**

time taken in rest frame of particles $\left(= \frac{distance}{speed} = \frac{5.0}{0.98c}\right)$ = 1.7 × 10^{-8} s **(1)**

time taken to decrease by ¼ = 2 half lives **(1)**

half life (= 1.7 × 10^{-8}/2) = 8.5 × 10^{-9} s **(1)**

[**alternatively**

time taken in rest frame of detectors $\left(= \frac{distance}{speed} = \frac{25.0}{0.98c}\right)$ = 8.5 × 10^{-8} s

time taken in rest frame of particles

(= 8.5 × 10^{-8} × $(1 - 0.98^2)^{1/2}$) =1.7 × 10^{-8} s)]

4

[5]

4 (a) (i) t_0 = 800 (s) **(1)**

(use of $t = t_0\left(1-\frac{v^2}{c^2}\right)^{-\frac{1}{2}}$ gives) $t = 800(1 - 0.994^2)^{-1/2}$**(1)**

= 7300 s **(1)**

(ii) distance (= $0.994ct$ = 0.994 × 3 × 10^8 × 7300)

= 2.2 × 10^{12}m **(1)** (2.18 × 10^{12}m)

(allow C.E. for value of t from (i))

4

(b) space twin's travel time = proper time (or t_0) **(1)**

time on Earth, $t = t_0\left(1-\frac{v^2}{c^2}\right)^{-\frac{1}{2}}$ **(1)**

$t > t_0$

[or time for traveller slows down compared with Earth twin] **(1)**

space twin ages less than Earth twin **(1)**

travelling in non-inertial frame of reference **(1)**

max 3

[7]

5 (a) Newton's laws obeyed in an inertial frame

[or inertial frames move at constant velocity relative to each other] **(1)**

suitable example (e.g. object moving at constant velocity) **(1)**

2

(b) (i) (use of $t = t_0\left(1-\frac{v^2}{c^2}\right)^{-1/2}$ gives) t_0 = 18 (ns) **(1)**

$t = 18 \times 10^{-9}\left(1-\frac{(0.995c)^2}{c^2}\right)^{-1/2}$ **(1)**

= 1.8 × 10^{-7} s **(1)**

(ii) time taken $\left(= \frac{\text{distance}}{\text{speed}}\right) = \left(\frac{108}{0.995 \times 3.0 \times 10^8}\right)$ = 3.6 × 10^{-7} s **(1)**

time taken = 2 half-lives, which is time to decrease to 25% intensity **(1)**

[alternative scheme: (use of $l = l_0\left(1 - \frac{v^2}{c^2}\right)^{1/2}$ gives) l_0 = 108 (m)

$l = 108\left(1 - \frac{(0.995c)^2}{c_2}\right)^{1/2}$ = 10.8 m **(1)**

time taken $\left(= \frac{10.8}{0.995c}\right)$ = 3.6 × 10^{-8} s

= 2 half-lives, which is time to decrease to 25% intensity **(1)**]

5

[7]

6 (a) (i) Distance travelled in muons' frame of reference

$= 10700(1-0.996^2)^{1/2} = 956$ m ✓

Time taken in muons' frame of reference = 3.2 μs ✓

This is 2 half-lives so number reaching Earth = 250 ✓

OR

Time in Earth frame of reference

$= 10700 / (0.996 \times 3 \times 10^8) = 3.581 \times 10^{-5}$ s ✓

Time taken in muons' frame of reference = 3.2 μs ✓

This is 2 half-lives so number reaching Earth = 250 ✓

OR

Half-life in Earth frame of reference

$= 1.6 \times 10^{-6} / (1-0.996^2)^{1/2} = 17.9 \times 10^{-6}$ s ✓

Time taken $= 35.8 \times 10^{-6}$ s ✓

This is 2 half lives so number reaching Earth = 250 ✓

OR

Distance travelled in muons' frame of reference

$= 10700(1-0.996^2)^{1/2} = 956$ m ✓

Distance the muon travels in one half-life in muons reference frame

$= 0.996 \times 3 \times 10^8 \times 1.6 \times 10^{-6} = 478$ m ✓

Therefore 2 half-lives elapse to travel 956 m so number = 250 ✓

OR

Decay constant in muon frame of reference

Or decay constant in the Earth frame of reference ✓

Uses the corresponding elapsed time and decay constant in

$N = N_0 e^{-\lambda t}$ ✓

Arrives at 250 ✓

All steps in the working must be seen

Award marks according to which route they appear to be taking

The number left must be deduced from the correct time that has elapsed in the frame of reference they are using

3

(ii)

	✓ if correct
For an observer in a laboratory on Earth the distance travelled by a muon is greater than the distance travelled by the muon in its frame of reference	✓
For an observer in a laboratory on Earth time passes more slowly than 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) Total energy = $9.11 \times 10^{-31} \times (3 \times 10^{8})^{2} / (1-0.98^{2})^{1/2}$ ✓

4.12×10^{-13} J seen to 2 or more sf ✓

Show that so working must be seen

2

(ii) Change = 7.5×10^{-14} J

V = 469 (470) kV allow ecf using their answer to (i) ✓

ecf is their ((i) −3.37) × 10^{-13}) / 1.6 × 10^{-19}

Using 4 × 10^{-13} gives 394 (390) kV

Using 3.9 × 10^{-13} gives 331(330) kV

Do not allow 1 sf answer

1

[7]

7 (a) speed of light in free space independent of motion of source and / or the observer✓
and of motion of observer

1

(b) laws of physics have the same form in all inertial frames
laws of physics unchanged from one inertial frame to another ✓

1

(c) time taken$\left(= \frac{\text{distance}}{\text{speed}} = \frac{34\text{ m}}{0.95 \times 3.0 \times 10^{8}\text{ m s}^{-1}}\right) = 1.2 \times 10^{-7}$ s✓

1

(d) $t = \frac{18\text{ ns}}{(1 - 0.95^{2}c^{2}/c^{2})^{1/2}}$ ✓

Allow substitution for this mark

1

time taken for π meson to pass from one detector to the other = 58 ns ✓

1

2 half-lives (approximately) in the detectors' frame of reference. ✓

1

two half-lives corresponds to a reduction to 25 % so 75% of the π mesons passing the first detector do not reach the second detector. ✓
OR
Appreciation that in the lab frame of reference the time is about 6 half-lives had passed✓

1

In 6 half-lives 1 / 64 left so about 90% should have decayed✓

Clear conclusion made
Either Using special relativity gives agreement with experiment
or Failure to use relativity gives too many decaying (WTTE)

1

[8]

8 (a) (i) Only Box Ticked: Mesons

1

(ii) (Muon) anti−neutrino symbol

Not electron anti−neutrino

Penalise incorrect subscript

1

(b) (i) Use of Speed = distance / time by rearrangement and 3.75×10^{-5} (s) seen
Or
$10.7 \times 10^3 \div 2.85 \times 10^8 = 3.75 \times 10^{-5}$ (s) seen
Or substitution **and** 3.75×10^{-5} (s) seen

No. of half-lives = $3.75 \times 10^{-5} \div 2.2 \times 10^{-6}$ = 17.065 or 17.07
not 17.05 not 17.06
At least 3 sf for answer 17.1

$3.75 \times 10^{-5} \div 17 = 2.208$ or 2.21 μs

At least 3 sf

Or

$17 \times 2.2 \times 10^{-6} = 37.4 \times 10^{-5}$ ***with comparison***

2

(ii) $2.5 \times 10^8 \times (1/2)^{17}$ or equivalent

1900 to 1910 (1910 maximum to 4 sf)

Answer consistent with any working seen

Use of $N = N_0 e^{-\lambda t}$ and $\lambda = \frac{\ln 2}{2.2 \times 10^{-6}}$ correct sub

Answer in range 1.8×10^3 to 1.91×10^3

(1820 minimum and 1910 maximum to 4 sf)

2

(iii) (Theory of special) relativity

Time dilation / length contraction treat as neutral

Not general relativity

1

(iv)
- Travelling close to speed of light less time passes in muon's reference frame for the journey (so fewer decay)
- Travelling close to speed of light so journey is shorter in length for the muon's frame of reference (so fewer decay)
- Travelling close to speed of light so muons are observed to travel further in a half−life (on Earth) than expected (so fewer decay during journey)
- Travelling close to speed of light so muon's half−life is observed to be longer (on Earth) (so fewer decay)

Allow:

• travelling close to speed of light so time is slower (for muons) so fewer decay

• travelling close to speed of light so time dilates so fewer decay

1

(v) Attempted use of $L = L_o (1-v^2/c^2)^{1/2}$ or $t = t_o /(1-v^2/c^2)^{1/2}$

Correct use of $L = L_o (1-v^2/c^2)^{1/2}$ ***and*** $(t_o = L/v) = 3341/2.85 \times 10^8$

or correctly makes t_o subject of $t = t_o /(1-v^2/c^2)^{1/2}$

$(t_o =)$ 1.17×10^{-5} or 1.2×10^{-5} (s)

Condone mix up on L / L_o or t / t_o

1.2×10^{-4} s gets 1 mark

Sub for L_o as 10.7×10^3

Or sub for $t = 3.75 \times 10^{-5}$

3

(vi) Use of $T_{½} = ln2/\lambda$ seen with sub for $T_{½}$
allow if seen in partial sub in $N = N_o e^{-\lambda t}$

Use of $N = N_o e^{-\lambda t}$ with $\lambda = 3.15 \times 10^5$ (or equivalent) and t = answer from b(v)

5.7×10^6 to 6.3×10^6
no ecf on answer

Or use of no half−lives = $\frac{b(v)}{2.2 \times 10^{-6}}$

And $\frac{2.5 \times 10^8}{2^{\frac{b(v)}{2.2 \times 10^{-6}}}}$

Only accept answers in this range

No ecf on answer

3

[16]

9 (a) no change in the fringe pattern on rotation **(1)**

the speed of light is the same in the two directions **(1)**

the speed of light from a light source on Earth is

unaffected by the motion of the Earth **(1)**

[or the speed of light is invariant

or independent of the motion of the source or observer] **(1)**

the laws of dynamics cannot be applied to light **(1)**

no ether **(1)**

(max 3)

(b) (i) time $\left(= \frac{\text{distance}}{\text{speed}} = \frac{16cT_{\text{one year}}}{0.8c} \right)$ = 20 yr **(1)**

(ii) $L_0 = 16c$ [or 16 light years] **(1)**

$$L\left(= L_0\left(1 - \frac{v^2}{c^2}\right)^{\frac{1}{2}}\right) = 16(1 - 0.8^2)^{\frac{1}{2}} (= 0.6 \times 16c) = 9.6c$$ **(1)**

(iii) Δt = 20 years **(1)**

$$\Delta t_0 = \Delta t\left(1 - \frac{v^2}{c^2}\right)^{\frac{1}{2}} = 20(1 - 0.8^2)^{\frac{1}{2}}$$ **(1)**

$= 0.6 \times 20 = 12$ yr $\therefore$ age = 21 + 12 = 33 yr **(1)**

(6)

[9]

10 (a) (i) the same or constant **(1)**
regardless of the speed of the observer or source **(1)**

(ii) physical laws have the same form in all frames **(1)**

(3)

(b) (i) $T_{\frac{1}{2}}$ or beams of mesons $= 8.6\text{ ns} \times \left(1 - \frac{v^2}{c^2}\right)^{-\frac{1}{2}}$ **(1)**

$= 8.6 \times (1 - 0.95^2)^{-\frac{1}{2}} = 27.5$ ns **(1)**

(ii) beam reduces to 25% in 2 half-lives **(1)**

$v(= 0.95\ c) = 2.85 \times 10^8$ m s^{-1} **(1)**

distance = 2×27.5 ns $\times 2.85 \times 10^8$ m s^{-1} **(1)**

= 15.6 m **(1)**

(6)

[9]