# WESLEY COLLEGE

By daring & by doing

ATAR Physics

Special Relativity, Standard Model and Cosmology Test 2019

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1. Sub-atomic particles called muons are produced in the upper atmosphere by collisions between cosmic rays and air molecules. The muons produced are moving at over 98% of the speed of light. In experiments using particle accelerators slow moving muons have been produced and found to have average lifetimes of 2.2 μs.

(a) Calculate how far muons produced in the upper atmosphere would be expected to travel during an average lifetime of 2.2 μs. (2)

$v = 0.98 \times 3.0 \times 10^8 \text{ ms}^{-1}$

$t = 2.2 \times 10^{-6} \text{ s}$

$s = vt$

$s = 646.8 \text{ m}$ ✓✓

(b) Calculate how far would the muons would actually travel due to the effect of time dilation. (4)

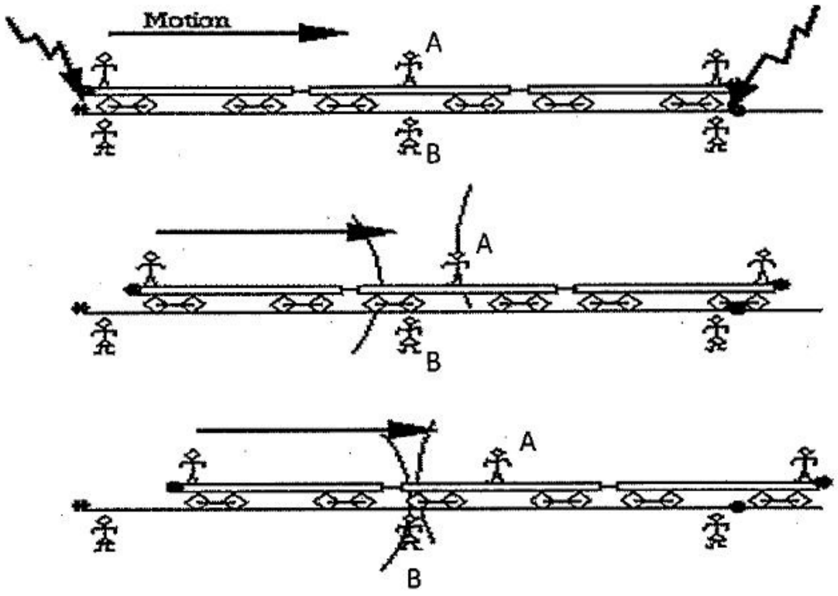
$$t = \frac{t_0}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{2.2\times10^{-6}}{\sqrt{1-(0.98)^2}} = 11.06\times10^{-6}\text{ s}$$ ✓✓

$s = vt$

$= 0.98 \times 3\times10^8 \times 11.06 \times 10^{-6}$

$= 3.25 \text{ km}$ ✓✓

2. The set of successive drawings below show two bolts of lightning hitting the front and back of a very fast train, which is moving to the right relative to observers on the ground next to the train track. The light from those lightning strikes moves towards observer A, standing exactly halfway along the train, and observer B, who is adjacent to A but standing on the ground next to the track when the lightning bolts strike.



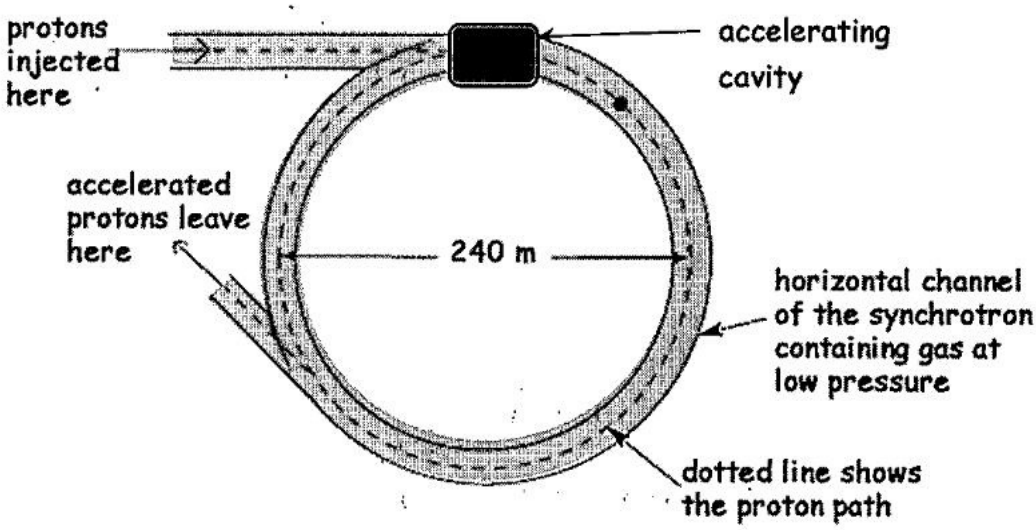

(a) Describe what the two observers, A and B, conclude about the order of the lightning strikes. (2)

A concludes the lightning bolt hits the front of the train before the back
B concludes the lightning bolts strike the front and back simultaneously.

(b) Explain why the two observers disagree about the order of the lightning strikes. (2)

They are in their own frames of reference and the speed of light is the same in both.
Each frame of reference is as valid as the others and their conclusions are correct from their viewpoints

3. A synchrotron uses a perpendicular magnetic field to contain protons as they circulate around a hollow ring; the protons pass around the ring and through the accelerating cavity thousands of times before finally leaving the ring at speeds approaching that of light. When passing through the accelerating cavity, the protons experience an effective potential difference of 24 kV each time.




(a) Calculate the gain in kinetic energy of the protons each time they pass through the accelerating cavity (2)

$\Delta KE = qV$

$= 1.6 \times 10^{-19} \times 24000 = 3.84 \times 10^{-15} J$

(b) Explain how the protons can continue to gain in kinetic energy every time they pass through the accelerating cavity, yet their speed can never exceed the speed of light. (2)

As a proton approaches the speed of light its mass increases rapidly.
This rapid increase in mass as $v \to c$ means K.E keeps increasing even though speed v increases incrementally

(c) A proton is accelerated in the synchrotron to 95.0% of the speed of light. Calculate the momentum of the proton. (2)

$$p = \frac{mv}{\sqrt{1 - \frac{v^2}{c^2}}} = \frac{1.67 \times 10^{-27} \times 0.95 \times 3 \times 10^8}{1 - (0.95^2)^{\frac{1}{2}}}$$

$= 1.52 \times 10^{-18} kgms^{-1}$

4. A spacecraft is moving away from Earth at a speed of 0.85c. The spacecraft fires a probe back towards Earth. As viewed from Earth the probe is moving at 0.60c towards Earth.

Determine the speed of the probe in the frame of reference of the spacecraft.

(3)

$$u' = \frac{u - v}{1 - \frac{uv}{c^2}} = \frac{-0.6 - 0.85}{1 - \frac{-0.6 \times 0.85}{c^2}}$$

$$u' = \frac{-1.45}{1 + 0.51} = 0.96c \quad (2.88 \times 10^8 \, ms^{-1})$$

5. The relatively nearby star Tau Ceti, which is the closest solitary G-class star like our Sun, lies *11.9 light-years* from Earth, and has five exoplanets, two of which lie in the "habitable zone" — that just-right range of distances that could support the existence of liquid water on the planets' surfaces. An interstellar spaceship from Earth is travelling to Tau Ceti at 90% of the speed of light.

(a) How far away is Tau Ceti (in *light-years)* to the astronauts on the spaceship? (2)

$$L = L_0 \left( \sqrt{1 - \frac{v^2}{c^2}} \right)^{\frac{1}{2}}$$

$$= 11.9 (1 - 0.9^2)^{\frac{1}{2}}$$

$$= 5.19 \text{ LY}$$

(b) How long will the spaceship take to reach Tau Ceti

(i) from the reference frame of observers on Earth? (1)

$$\frac{11.9}{0.9c} = 13.2 \text{ years.}$$

(ii) from the reference frame of the astronauts on the spaceship? (1)

$$\frac{5.19}{0.9c} = 5.76 \text{ years.}$$

6. A lead ion ($Pb^{2+}$) of mass $3.44 \times 10^{-25}$ kg is accelerated to a speed of 77% the speed of light in a particle accelerator. The total energy of the lead ion is given by its mass-energy equivalence which is the sum of its rest energy ($E = mc^2$) and its kinetic energy.

Calculate the kinetic energy of the lead ion. (3)

$$E = \frac{mc^2}{\sqrt{1-\frac{v^2}{c^2}}} \qquad E = mc^2 - kE$$

$$kE = \frac{mc^2}{\sqrt{1-\frac{v^2}{c^2}}} - mc^2$$ ✓

$$k.E = \left( \frac{3.44\times10^{-25} \times (3\times10^8)^2}{\sqrt{1-\frac{0.77^2}{1}}} \right) - 3.44\times10^{-25} \times (3\times10^8)^2$$

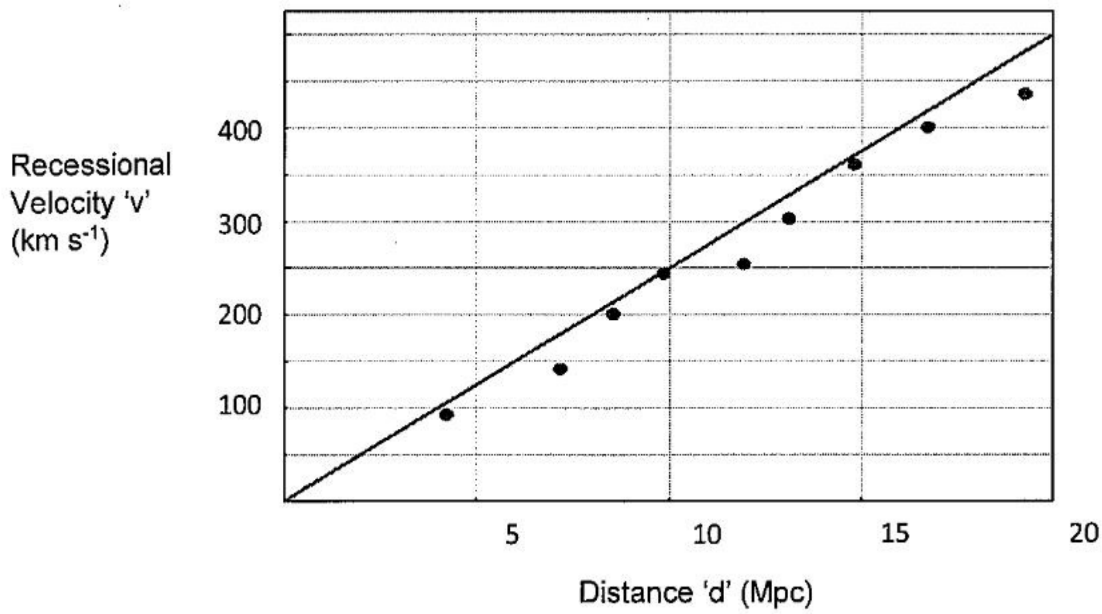
$$k.E = 1.76\times10^{-8} J$$

7. Edwin Hubble calculated recessional velocities of galaxies and estimated distances to the galaxies from earth. The data yielded the first iteration of Hubble's Law stating the following relationship:

$v = H_o \times d$ where: v = recessional velocity of the galaxy ($km\ s^{-1}$);

$H_o$ = Hubble's constant;

d = distance to the galaxy (Mpc).




(a) Use the graph to estimate Hubble's Constant ($H_o$) for this data in $kms^{-1}Mpc^{-1}$. (2)

$$H_o = \frac{500-0}{20-0} = 25\,kms^{-1}Mpc^{-1}$$

(b) Hubble's Constant can be used to estimate the age of the Universe (T).

$$T = \frac{1}{H_0}$$

Use this equation and the fact that 1 Mpc = $3.08 \times 10^{22}$ m to calculate the age of the Universe in years.
[If you could not calculate a value for Hubble's Constant in part (b), use a value of 30 $kms^{-1}\ Mpc^{-1}$].

$$H_o = 25 \times \frac{1000}{3.08\times10^{22}} = 8.11\times10^{-19}\,s^{-1}$$ (3)

$$Time = \frac{1}{8.11\times10^{-19}} = 1.23\times10^{18}\,s$$

$$Time = \frac{1.23\times10^{18}}{3600\times24\times365}$$

$= 3.91 \times 10^{10}$ years. (or $3.26\times10^{10}$ years if using $30\,kms^{-1}Mpc^{-1}$)

(c) The recessional velocities of galaxies confirmed that the Universe is continuing to expand after the Big Bang. Write down two other pieces of evidence for the Big Bang Theory. (2)

- Presence of hydrogen and Helium in the Universe
- Cosmic microwave background radiation.

(d) Red shift of light is another piece of evidence for the expansion of the universe. Spectral lines on an emission spectrum of light coming from a distant galaxy have been Doppler shifted from 420nm to 395nm. What is the recessional velocity of the galaxy in $kms^{-1}$? (2)

$$z = \frac{\lambda - \lambda_0}{\lambda_0} = \frac{v}{c}$$

$$\frac{420 - 395}{395} = \frac{v}{3.0\times10^8\,ms^{-1}\ (3.0\times10^5\,kms^{-1})}$$

$$v = 1.9\times10^7\,ms^{-1}$$

$$= 1.8\times10^4\,kms^{-1}$$

8. There are 6 different quarks, which are shown in the table below. Quarks exist in combination as composite particles called hadrons. There are two classes of hadrons – baryons and mesons.

| NAME | SYMBOL | Charge (Q) | Baryon Number (B) | Strangeness (S) | Charm (c) | Bottomness (b) | Topness (t) |
|---|---|---|---|---|---|---|---|
| *Up* | u | $+\frac{2}{3}e$ | $\frac{1}{3}$ | 0 | 0 | 0 | 0 |
| *Down* | d | $-\frac{1}{3}e$ | $\frac{1}{3}$ | 0 | 0 | 0 | 0 |
| *Strange* | s | $-\frac{1}{3}e$ | $\frac{1}{3}$ | -1 | 0 | 0 | 0 |
| *Charmed* | c | $+\frac{2}{3}e$ | $\frac{1}{3}$ | 0 | +1 | 0 | 0 |
| *Bottom* | b | $-\frac{1}{3}e$ | $\frac{1}{3}$ | 0 | 0 | -1 | 0 |
| *Top* | t | $+\frac{2}{3}e$ | $\frac{1}{3}$ | 0 | 0 | 0 | +1 |

(a) Give the quark composition of each of the following hadrons: (2)

(i) the baryon $\Lambda^{C+}$ which has Q = +1, B = 1, S = 0, c = +1 and b = t = 0 udc

(ii) the meson $D_s^+$ which has Q = +1, B = 0, S = +1 and c = +1 and b = t = 0 $c\bar{s}$

(b) The quark composition of some baryons and mesons is given in the table below. Antiparticles are represented by being underlined.

| Baryons | | | Mesons | | |
|---|---|---|---|---|---|
| Name | Symbol | Quarks | Name | Symbol | Quarks |
| proton | p | uud | pion-plus | $\pi^+$ | $u\underline{d}$ |
| neutron | n | udd | pion-minus | $\pi^-$ | $d\underline{u}$ |
| lambda-zero | $\Lambda^0$ | uds | kaon-plus | $K^+$ | $u\underline{s}$ |
| sigma-plus | $\Sigma^+$ | uus | kaon-minus | $K^-$ | $s\underline{u}$ |
| sigma-minus | $\Sigma^-$ | dds | kaon-zero | $K^0$ | $d\underline{s}$ |

Given that each type of quark is conserved in the following particle reaction, predict the quark composition and identity of the missing particle. (2)

$\pi^-$ + p -> $K^0$ + $\Lambda^0$

$d\bar{u} + uud \rightarrow d\bar{s} + uds$

i.e. $d(\bar{u}u)ud \rightarrow d(s\bar{s})du$

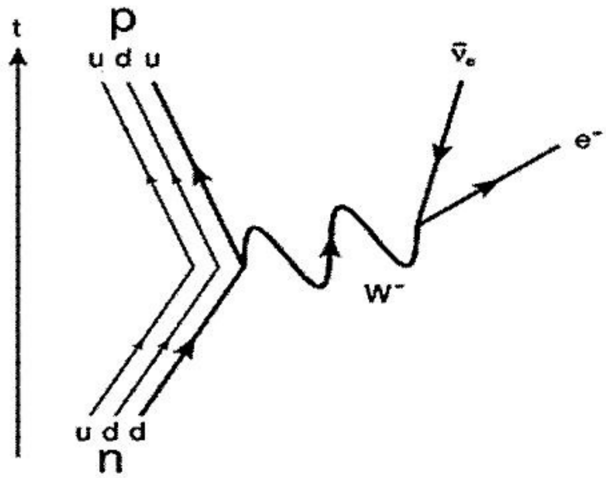
uud = proton

9. ~~11~~. All matter is made of hadrons and leptons. What are two characteristics of leptons that make them different to hadrons. (2)

Any 2.

- Lighter in mass
- fundamental particle not made of quarks.
- do not interact by the strong nuclear force.

10. Neutron decay is shown in the particle interaction diagram below.




(a) Neutron decay is an example of which of the following fundamental interactions? (circle your choice for the correct answer) (1)

**strong** **weak** **electromagnetic**

(b) The neutron decay shown in the diagram above consists of two consecutive steps. Briefly describe the particle interactions in each of these steps. (2)

Step 1: A down quark in the neutron changes into an up quark with the emission of a $W^-$ boson

Step 2: The $W^-$ boson decays into an electron and an anti electron neutrino

(c) Write an equation for the overall neutron decay reaction shown in the particle interaction diagram above. (1)

$n \rightarrow p + e + \bar{\nu}_e$

(d) Show that each of the quantities of charge, baryon number and lepton number is conserved during neutron decay. (3)

$0 = +1 + (-1) + 0$

Baryon no. $+1 = +1 + 0 + 0$

Lepton no. $0 = 0 + (+1) + (-)$

**End of test**