YEAR 12 PHYSICS
ASSIGNMENT 7 - STANDARD MODEL

Name: SOLUTIONS **Mark:** ___ / 101

1. Sirius appears as the brightest star in the night sky. It is actually a binary star consisting of Sirius A, a large blue-white star, and Sirius B, a white dwarf. Our view of the Sirius star system is such that there are times when Sirius B is coming toward us and times when it is going away from us. When Sirius B is moving toward us:

(a) Sirius A will be (1 mark)

A moving toward us, relative to Sirius B.
B moving away from us, relative to Sirius B.

Your answer B (1)

(b) Compared to the speed of light approaching us from Sirius A, the speed of the light approaching us from Sirius B will be (1 mark)

A the same.
B less.
C greater.

Your answer A (1)

(c) An astronomer views a spectrum of the visible light from Sirius B. Describe **one** feature of this spectrum that would indicate Sirius B is moving toward the astronomer. (2 marks)

There will be absorption lines. (1)

They will be blue-shifted. (1)

(d) Big Bang theory predicts the Sirius system should be (1 mark)

A moving toward us.
(1) B moving away from us.
C keeping a constant distance.

2. Two spaceships, 'Albert' and 'Max' are travelling toward each other. Each has a speed of 0.750c as measured in the Earth's reference frame.

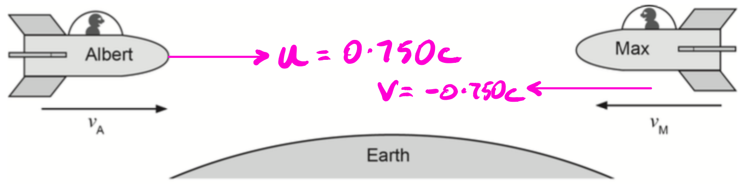
+VE

observer

$u = 0.750c$

$V = -0.750c$

$u' = ?$



Calculate the velocity of Max as measured by the crew on spaceship Albert. (4 marks)

$$u' = \frac{u - v}{1 - \frac{uv}{c^2}} \quad (1)$$

$$= \frac{0.750c - (-0.750c)}{1 - \frac{(0.750c)(-0.750c)}{c^2}} \quad (1)$$

$$= \frac{-1.50}{1.563} \quad (1)$$

$$= \underline{-0.960c} \quad (1)$$

3. Muons are created in the upper atmosphere with speeds of 0.990c or more. Their average lifetime is 2.20 μs measured at low speeds in the laboratory. A simple calculation shows that most should only travel about 660 m before decaying. Thus, very few muons should ever reach sea level.

(a) Using relativistic mechanics, calculate how far a muon can travel according to an observer on Earth. (4 marks)

observer

$u = 0.990c$

$t_0 = 2.20 \mu s$

$$t = \frac{t_0}{\sqrt{1 - \frac{v^2}{c^2}}} \quad (1)$$

$$= \frac{2.20 \times 10^{-6}}{\sqrt{1 - \frac{(0.990c)^2}{c^2}}} \quad (1)$$

$$= 1.56 \times 10^{-5} \text{ s} \quad (1)$$

$$v = \frac{s}{t}$$

$$\Rightarrow s = vt$$

$$= (0.990)(3.00 \times 10^8)(1.56 \times 10^{-5})$$

$$= \underline{4.63 \times 10^3 \text{ m}} \quad (1)$$

(b) Explain why many more muons reach the surface of Earth than predicted classically. (2 marks)

The muon's lifetime is dilated according to an observer on Earth and/or the distance travelled is contracted from the muon's reference frame. (1)

This results in many more reaching the surface. (1)

4. An electron microscope creates a coherent beam of electrons which then travels through two narrow slits. The resulting interference pattern is detected on a photographic plate. The speed of the electrons is 1.00% of the speed of light.

(a) Show that the de Broglie wavelength of the electrons used is 2.43×10^{-10} m. (2 marks)

$$\lambda = \frac{h}{p} = \frac{h}{mv}$$

$$= \frac{6.63 \times 10^{-34}}{(9.11 \times 10^{-31})(0.0100 \times 3.00 \times 10^{8})} \quad (1)$$

$$= \underline{2.43 \times 10^{-10}\ \text{m}} \quad (1)$$

(b) Describe what you expect to see on the photographic plate. (2 marks)

There will be a series of bright and dark fringes. (1)

There will be a bright line in the centre. (1)

(c) Explain the behaviour of the electrons in this experiment. (2 marks)

The electrons display wave behaviour. (1)

The behaviour could be:

- diffraction
- constructive and destructive interference (either OK - 1 mark)

(d) If the experiment were to be repeated using protons, at what speed would a proton need to travel to have the same de Broglie wavelength as the electrons? (2 marks)

$$\lambda = \frac{h}{p} = \frac{h}{mv} \Rightarrow v = \frac{h}{m\lambda}$$

$$= \frac{6.63 \times 10^{-34}}{(1.67 \times 10^{-27})(2.43 \times 10^{-10})} \quad (1)$$

$$= \underline{1.63 \times 10^{3}\ \text{ms}^{-1}} \quad (1)$$

(e) Calculate the potential difference required for the electron microscope to accelerate the electrons to 1.00% of the speed of light. (4 marks)

$$W = Vq = \tfrac{1}{2}mv^2 \quad (1)$$

$$\Rightarrow V = \frac{mv^2}{2q} \quad (1)$$

$$= \frac{(9.11 \times 10^{-31})(0.0100 \times 3.00 \times 10^{8})^2}{2(1.60 \times 10^{-19})} \quad (1)$$

$$= \underline{25.6\ \text{V}} \quad (1)$$

5. The elementary particles of the Standard Model are shown in the data sheet.

(a) If up (u) and down (d) quarks are the building blocks of nucleons, suggest a combination of three quarks that would produce a

(i) proton: UUD (1) (1 mark)

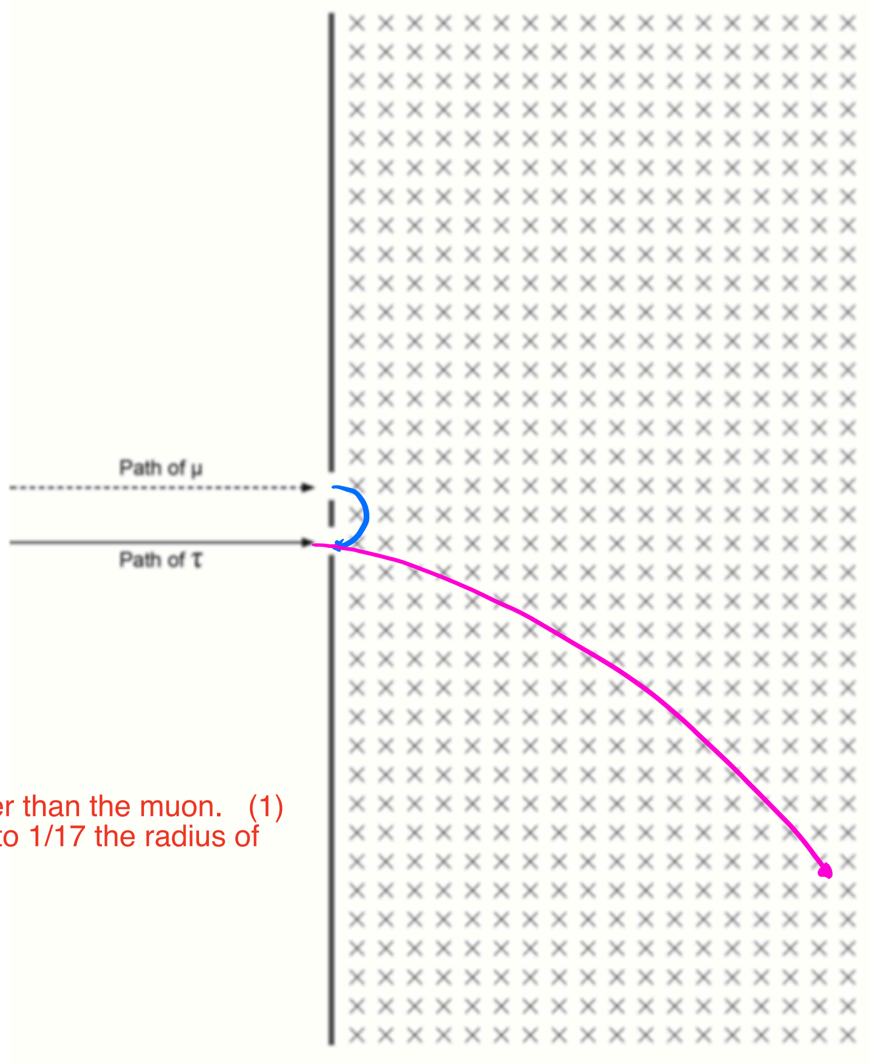
(ii) neutron: UDD (1) (1 mark)

(b) Identify **one** type of gauge boson and describe its role in the nucleus. (2 marks)

Gluon: provides strong force between quarks.
Photon: provides electrostatic force between protons.
Higgs boson: provides mass to particles.
W, Z boson: provides the weak nuclear force (beta decay).

Identifies one gauge boson (1)
Good description (1)

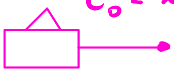
(c) Muons and taus are created in a particle accelerator and accelerated to the same velocity. Sketch their paths if the two particles were directed into a magnetic field as shown in the diagram below. (4 marks)



Muon bends down. (1)
Tau bends down. (1)
Tau path radius is greater than the muon. (1)
Muon path radius close to 1/17 the radius of the tau path. (1)

6. A deep-space probe moves away from the Earth with a speed of 0.550c. In its frame of reference, an antenna on the probe rotates every 23.0 s. Calculate the time for **one** rotation when observed from Earth. (2 marks)

$t_0 = 23.0\,s$



$v = 0.550c$

$$t = \frac{t_0}{\sqrt{1-\frac{v^2}{c^2}}}$$

$$= \frac{23.0}{\sqrt{1-\frac{(0.550c)^2}{c^2}}} \quad (1)$$

$$= \underline{27.5\,s} \quad (1)$$

7. Photons with sufficient energy can, on interacting with matter, produce an electron-positron pair.

(a) (i) Show that the lepton number is conserved in such an interaction. (3 marks)

$\gamma = e^- + e^+$ (1)

LHS: $L = 0$

RHS: $L = -1 + 1 = 0$ } (1)

$\therefore$ L is conserved (1)

(ii) Given $E = mc^2$, determine the minimum frequency of a photon that could produce an electron-positron pair. (4 marks)

$E = hf = mc^2$ (1)

$$\Rightarrow f = \frac{mc^2}{h} = \frac{(2\times 9.11\times 10^{-31})(3.00\times 10^{8})^2}{(6.63\times 10^{-34})} = \underline{2.47\times 10^{20}\,Hz}$$

(1) (1) (1)

A neutron will decay into a proton and an electron as shown in the equation below.

$$n \rightarrow p^+ + e^- + ?$$

(b) (i) Demonstrate that the baryon number is preserved in the way that the equation is written above but the lepton number is not. (2 marks)

	LHS	RHS
baryon	1	1+0
lepton	0	0+1

$\Rightarrow$ LHS = RHS (1)

$\Rightarrow$ LHS $\neq$ RHS (1)

(ii) Identify the third particle in the decay to ensure that the lepton number is conserved. (1 mark)

$\bar{\nu}_e$ (electron anti-neutrino) (1)

8. Use the Standard Model in the Formulae and Data Booklet provided to answer the following questions.

(a) Identify the elementary particle responsible for mediating each of the following phenomena and complete each sentence. (3 marks)

The elementary particle responsible for the weak force is the W or Z boson (1)

The elementary particle responsible for the strong force is the Gluon (1)

The elementary particle responsible for the electrostatic force is the Photon (1)

A table of the characteristics of the four forces can be drawn as shown.

Force	Relative strength	Range (m)
Strong	1	10^{-15}
Weak	10^{-6}	10^{-18}
Electromagnetic	10^{-2}	infinite
Gravitational		infinite

(b) (i) The relative strength of the gravitational force would **best** be described as: (1 mark)

A 10^{12}.
B 10^{-4}.
C 10^{-12}.
D 10^{-38}.

Your answer C or D (1)

(ii) Give an appropriate reason for your choice. (2 marks)

Gravitational force does not contribute (too small) to subatomic interactions. (1)

Must be significantly lower strength than strong or weak force. (1)

(Other explanations could compare electromotive force with gravitational force.)

(c) The order of evolution of forces directly after the big bang is best thought of as: (1 mark)

A gravitational first, then strong and weak last.
B weak first, then strong and gravitational last.
C strong first, then weak and gravitational last.
D simultaneous, i.e. all forces were created at the same moment.

Your answer A (1)

(d) A graviton is the proposed particle that mediates gravity but is as yet undiscovered. Suggest a characteristic for the graviton and give a reason why. (2 marks)

Zero mass. (1)
Range of the force is infinite and force weakens with 1/r2; therefore must have 0 mass (could also explain that as force acts at an infinite distance the particle must travel at c, therefore mass = 0). (1)

or

Zero charge. (1)
Would already have been detected as charged particles are identifiable through interaction with magnetic fields. (1)

9. Positron emission topography (PET) is a high-resolution gamma ray medical imaging technique and is useful for scanning soft tissue of the human body.

Fluorine-18 is a radioisotope commonly used in PET. Fluorine-18 is produced via the proton bombardment of the stable isotope oxygen-18 in a cyclotron.

The unstable fluorine-18 used in PET decays back to oxygen-18 as shown in the equation below.

$$^{18}_{9}\mathrm{F} \rightarrow {}^{18}_{8}\mathrm{O} + {}^{0}_{+1}\mathrm{e} + \nu_e$$

(a) Use the equation above to describe how the nucleus of the fluorine-18 decays to produce oxygen-18. Name the other particles produced. (3 marks)

A proton turns into a neutron. (1)

A positron is emitted (1)

and an electron neutrino. (1)

(b) Name the force and force particle that mediate the interaction described in part (a). (2 marks)

Force: weak (1)

Force particle: W+ boson (accept W or Z boson) (1)

(c) Use your knowledge of the Standard Model to prove that this emission obeys the conservation of baryon number and charge. Assume all quarks have a baryon number equal to ⅓. (4 marks)

$$^{1}_{1}p \rightarrow {}^{1}_{0}n + {}^{0}_{+1}e + \nu_e$$

	LHS	RHS	
baryon	+1 (1)	+1 + 0 + 0 (1)	⇒ LHS = RHS
charge	+1 (1)	0 + 1 + 0 (1)	⇒ LHS = RHS

Can also consider the whole atom on each side for both baryon and charge number.

e.g. + 18 for F (18 baryons), +18 for O (18 baryons)

One of the products from the decay of fluorine-18 then interacts with the electrons of the human body to create two gamma rays that travel in opposite directions to each other. These gamma rays are detected and used to form images of tissues in the human body.

(d) Discuss the interactions that must occur to produce two gamma rays travelling in opposite directions to each other. (5 marks)

A positron and an electron must meet/interact due to electromagnetic forces. (1)

As a positron is an electron anti-particle, (1)
they will annihilate, producing energy in the form of photons. (1)

To conserve energy, two high-energy photons must be produced (1)
and travel in opposite directions to conserve momentum. (1)

10. In 2012, scientists at the European Organisation for Nuclear Research (CERN) in Switzerland claimed to have found the Higgs boson. They measured its rest energy to be 126 GeV. Show that the mass of the Higgs boson is 2.24×10^{-25} kg. (4 marks)

$$E = mc^2$$

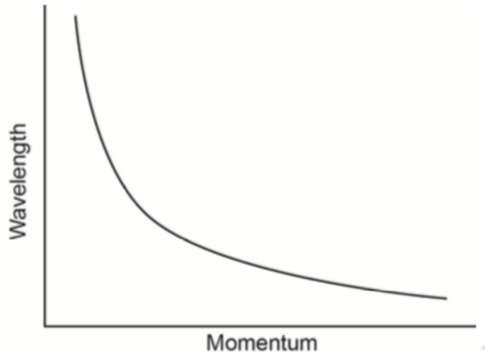
$$\Rightarrow \quad m = \frac{E}{c^2} \quad (1)$$

Conversions (1)

$$= \frac{(126 \times 10^9)(1.60 \times 10^{-19})}{(3.00 \times 10^8)^2} \quad (1)$$

$$= \underline{2.24 \times 10^{-25}} \text{ kg} \quad (1)$$

11. If we plot the de Broglie wavelength of a subatomic particle against its momentum, we get the graph shown below. This applies to velocities less than 5% of the speed of light.



(a) Give a possible relationship between wavelength and momentum based upon the shape of the graph. (1 mark)

$\lambda \propto \frac{1}{p}$ (inverse relationship) (1)

(b) Describe how the data used to generate the graph could be reorganised to produce a straight-line graph. (2 marks)

Plot λ vs $\frac{1}{p}$ (or p vs $\frac{1}{\lambda}$) (2)

(Must mention both variables.)

(c) What would the gradient of the straight-line from part (b) represent? (1 mark)

Planck's constant for λ vs $\frac{1}{p}$. (1)

($\frac{1}{h}$ for p vs $\frac{1}{\lambda}$)

(d) Ignoring relativistic effects, calculate the momentum of a particle with a wavelength of 2.50×10^2 nm. (4 marks)

$$\lambda = \frac{h}{p}$$

$$\Rightarrow p = \frac{h}{\lambda} \quad (1)$$

$$= \frac{(6.63 \times 10^{-34})}{(2.50 \times 10^{-7})} \quad (1)$$

$$= \underline{2.65 \times 10^{-27} \text{ kgms}^{-1}} \; (\text{Ns}, \text{Jsm}^{-1}) \quad (1)$$

Units (1)

12. Chloe is piloting the spaceship *Antilles*. It is 1.10 km long and travelling at 0.800c past a spaceport controlled by Zhang. Zhang needs to measure the speed of passing spaceships. Chloe steers the spaceship between two beacons 1000 m apart as measured by Zhang. The beacons are placed parallel to the *Antilles'* path. Both Chloe and Zhang start their timers when the front of the *Antilles* reaches the first beacon.

(a) Calculate the time elapsed on Zhang's clock (as observed by Zhang) when the front of *Antilles* reaches the second beacon. (1 mark)

Zhang is the stationary observer.

$l_o = 1000\,m$

$$v = \frac{s}{t}$$

$$\Rightarrow t = \frac{1.00 \times 10^3}{(0.800)(3.00 \times 10^8)}$$

$$= \underline{4.17 \times 10^{-6}\,s} \quad (1)$$

(b) Calculate the distance Chloe observes between the beacons before she passes the first beacon. (2 marks)

Chloe is in the moving reference frame.

$l_o = 1000\,m$

$$l = l_o \sqrt{1 - \frac{v^2}{c^2}}$$

$$= (1.00 \times 10^3) \sqrt{1 - \frac{(0.800c)^2}{c^2}} \quad (1)$$

$$= \underline{6.00 \times 10^2\,m} \quad (1)$$

(c) At one stage, Zhang observes *Antilles* fits completely between the two beacons. Chloe says that at no time did the spaceship completely fit between the beacons. Explain how they can both be correct, and why. (4 marks)

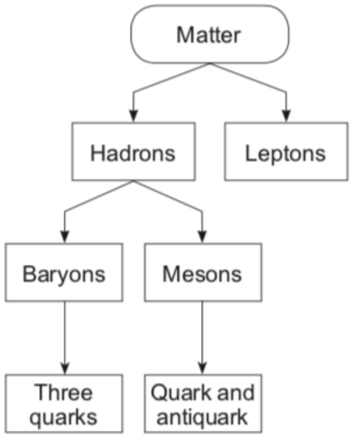
Observing the whole of Antilles between the beacons at a particular time requires you to measure the positions of the front and back simultaneously. (1)

Simultaneity is not the same for each observer. (1)

Due to length contraction, Zhang observes length of Antilles as 660 m so it fits easily between the beacons. (1)

Chloe observes distance between the beacons contract to 600 m so Antilles does not fit. (1)

13. The table below shows the classification of matter.



A kaon is a subatomic particle first detected in cosmic rays in 1947. There are four types:

K^- a negatively-charged particle consisting of a strange quark and an up antiquark
K^+ a positively-charged antiparticle of the **K^-** kaon
K^0 a neutrally-charged particle consisting of a strange antiquark and a down quark
K^{0-} the antiparticle of the **K^0**.

(a) Are kaons classified as baryons or mesons? (1 mark)

mesons (1)

(b) Justify your answer to part (a). (2 marks)

Mesons are comprised of two quarks, one quark and one antiquark. (1)

Kaons are made up of a strange and an up antiquark. (1)

(c) Name the quarks that make up the K^{0-} particle. (2 marks)

strange quark (1)

down antiquark (1)

(d) K^- particles have a mean lifetime of 1.238×10^{-8} s in their own frame of reference. Kaons produced in a particle accelerator were found to be moving at $0.850c$. Calculate their mean lifetime in the frame of reference of a stationary observer. (3 marks)

Observer

$\circ \longrightarrow v = 0.850c$

$t_0 = 1.238 \times 10^{-8}$ s (1)

$$t = \frac{t_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$= \frac{1.238 \times 10^{-8}}{\sqrt{1 - \frac{(0.850c)^2}{c^2}}} \quad (1)$$

$$= \underline{2.35 \times 10^{-8} \text{ s}} \quad (1)$$

Kaons were produced in the Tevatron, a particle accelerator in the United States. Protons were accelerated in a linear accelerator (LINAC) containing a strong electric field. Then they were injected into the circular main injector ring to be accelerated to energies of up to 1.00 TeV.

(e) With the use of appropriate equations, explain how the protons were:

(i) accelerated to high speeds in the linear accelerator. (2 marks)

Charged particles are accelerated to higher speeds using electric fields. (1)

From F = Eq = Vq/d = ma, a = Vq/md. The electric field generated by the huge potential difference V accelerates the protons. (1)

(ii) held in circular paths in the main ring. (2 marks)

Charged particles are held in circular paths by strong magnetic fields. (1)

From r = mv/Bq, the external magnetic field interacts with the magnetic field of the moving protons to produce a perpendicular centripetal force that holds the protons in a constant path of radius r. (1)