KINGSWAY CHRISITAN COLLEGE

12 ATAR Physics 2016
End of Unit Test

Relativity and Quantum Physics

Name: *MARKING KEY*

NOTE: Formula and constants sheet may be used.
All answers are to be accurate to three significant figures.
Marks will be given to correct working and diagram despite an incorrect final answer.
Conversely, working is required to demonstrate how a correct final answer was arrived at.

SECTION A	29	
SECTION B	38	
SECTION C	13	
TOTAL	**80**	

Section A: Short Answers

Question 1 (3 marks)

When demonstrating the photoelectric effect, a beam of light is shone onto a clean metal surface. If the light is above a certain threshold frequency it causes electrons to be ejected from the surface. Explain if this indicates that light is behaving as a particle or a wave.

Behaving as a particle (quantum) ½

Wave theory predicts that electrons would be ejected at any frequency (given enough intensity or time)

The threshold frequency suggests that the minimum energy required to eject the electron is related to frequency (not to intensity or time)

Where the threshold frequency equates to the minimum energy required ½

(3 marks)

Question 2 (3 marks)

According to the theory of special relativity, some properties are dependent on the frame of reference in which they are observed. If an observer is observing the events listed in column 1, indicate in column 2 if the event is:

Always the same or
May sometimes be different

Column 1	Column 2
The **distance** between two given events	*Sometimes different*
The **time interval** between two given events	*Sometimes different*
The **mass** of an electron measured at rest	*The same*

(3 marks)

Question 3 (4 marks)

Ultraviolet radiation is produced when an electron moves form one energy level in an atom to a different energy level.

(a) Would the energy be emitted as the electron moves from a higher level to a lower level or from a lower level to a higher level?

Energy is emitted as the electron moves from a higher level to a lower level.

(1 mark)

(b) Explain why you have chosen your answer to Q1(a) above.

For energy to be emitted the electron must 'give up' energy that it has acquired by being in a higher energy level. For the electron to produce energy with a frequency of ultra violet light the electron must have been previously promoted to the higher level so it will release energy as it 'falls' to the lower energy level.

(1 mark)

(c) Estimate the difference in energy levels (in electron volts) that would be required to produce ultra violet radiation.

(2 marks)

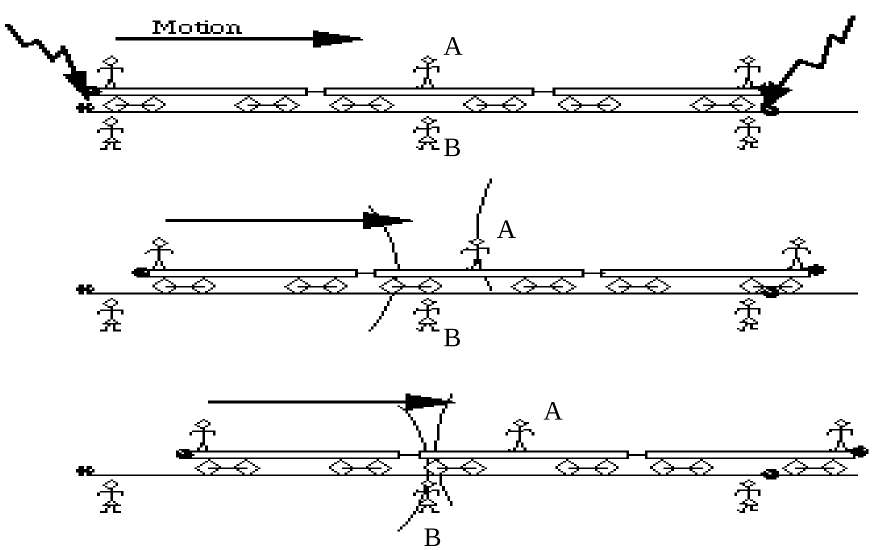
$E = h \times f$

$E = (6.63 \times 10^{-34}) \times 10^{16} = 6.63 \times 10^{-18}\ J$

$E = \dfrac{6.63 \times 10^{-18}}{1.60 \times 10^{-19}} = \underline{41.4\ eV}$

Question 4 (4 marks)

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.

Observer A *concludes that the lightning bolts struck the* ***front before the back*** *of the train*
(but that they would seem simultaneous to B as he is moving to the left away from the first lightning strike)

__Observer B__ concludes that the two lightning bolts struck __simultaneously__
(but that the strike on the front of the train would seem to be first to A as he is moving to the right towards the first lightning strike)

(2 marks)

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

The two observers, moving at some speed relative to one another, disagree because each observer, in their own frame of reference, measures the __speed of light__ to be the __constant__ value of 3×10^{8} m/s
Each observer's frame of reference is as valid as the other's __– both observers are correct__ in their conclusion about the order of the lightning strikes from their own viewpoints

(2 marks)

Question 5 (4 marks)

Some street lamps produce yellow/orange colour instead of the usual white light. Explain how these lamps are able to emit this coloured light.

Street lamps that emit coloured light are likely to have transitions that produce energy corresponding to frequencies in the __yellow__/orange part of the visible spectrum. Electrons are __promoted__ to energy levels within the atom and when they __return__ to a lower energy level photons of a __discrete__ frequency is emitted.

(4 marks)

Question 6 (4 marks)

(a) ESTIMATE the energy of an X ray photon.

(2 marks)

$E = hf$

Energy $= (6.64 \times 10^{-34}) \times 10^{18} = \underline{6.6 \times 10^{-16}}$ J

(range 6×10^{-15} to 6×10^{-17} J)

(b) How many photons would you receive during an X ray examination if the X ray tube, rated at 2 mW, was activated for 2 secs?

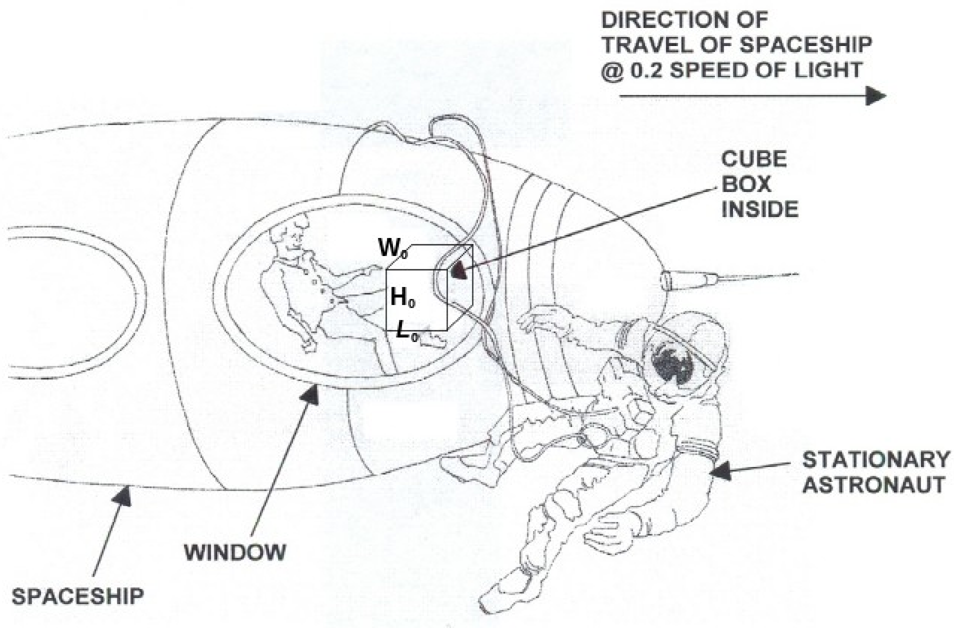
(2 marks)

Number of photons $= \dfrac{4 \times 10^{-3}}{6 \times 10^{-16}} = \underline{6.6 \times 10^{12}}$

(allow range 6.6×10^{11} *to* 6.6×10^{13}*)*

Question 7 (4 marks)

A spaceship travelling at 20% of the speed of light (i.e. 0.2 x c) contains a cube shaped box. An astronaut floating freely in space outside the spaceship views the box through a window as the spaceship passes and records its dimensions as L, W and H. A passenger on the spaceship records the dimensions of the box as L_o, W_o and H_o.



(a) Which of the following options best describes the dimensions of the box as observed by the astronaut outside the spaceship compared to the measurements made by the passenger?

A. $L<L_o$, $W<W_o$, $H=H_o$
B. $L>L_o$, $W=W_o$, $H=H_o$
C. $L<L_o$, $W=W_o$, $H=H_o$
D. $L<L_o$, $W<W_o$, $H<H_o$

Answer *C* *(1 mark)*

(b) Explain why you selected your answer.

*For an object travelling at **relativistic** speed, the length in the direction of travel (as seen by a stationary observer) is **shorter**. The other dimensions remain **unchanged**.*

(3 marks)

Question 8 (3 marks)

Global positioning systems (GPS) are used to measure distances on Earth. To provide accurate and reliable information, clocks on GPS satellites must be accurate within 20 to 30 nanoseconds per day. Relativity theories indicate that clocks on GPS satellites will run faster than clocks on the Earth by about 446 picoseconds per second. If this error were not taken into account, calculate the distance error per second the GPS radio signal would produce?

(3 marks)

$c = 3 \times 10^{8}$ m s^{-1}

time gain = 446×10^{-12} s

In 446×10^{-12} s light travels a distance given by:

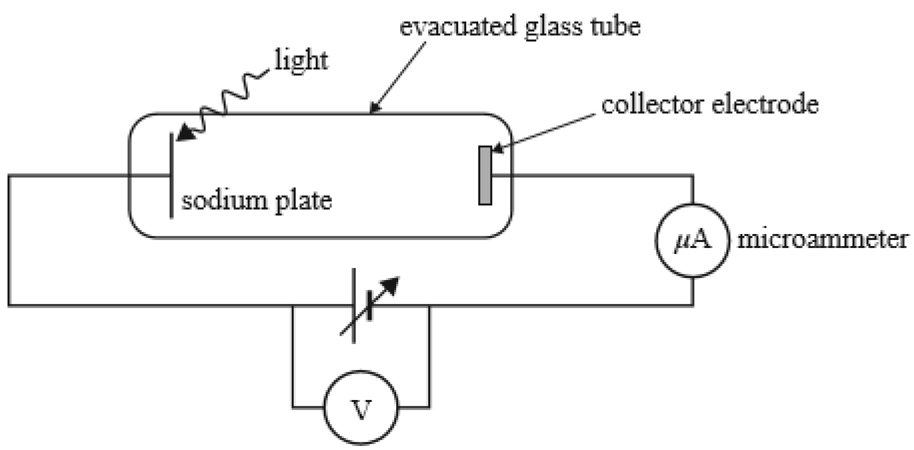
$s = v \times t = (3 \times 10^{8}) \times (446 \times 10^{-12}) = 0.134$ m

The distance error per second is 13.4 cm

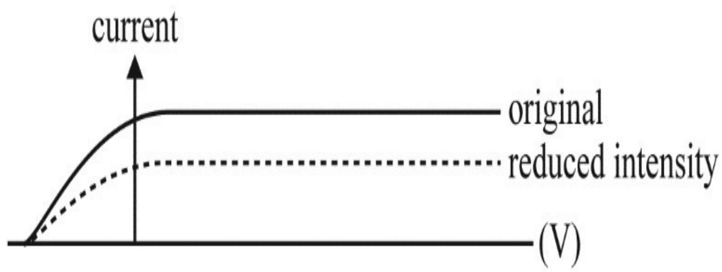
Section B: Problem Solving

Question 10 (7 marks)

Students are investigating the photoelectric effect by shining monochromatic light with a frequency of 1.00×10^{15} Hz onto a sodium plate. Their apparatus is shown below.



The following shows a graph of the relationship between the photocurrent and the reading on the voltmeter.



(a) Use the information in the graph to calculate the maximum kinetic energy (in joules) of the photoelectrons.

(1 mark)

Since it required a 1.85 V reverse potential to stop the electrons, the electrons must have had 1.85 eV of kinetic energy.

To convert this to joules, multiply by 1.6×10^{-19}

which gives $\underline{2.96 \times 10^{-19}}$ *J.*

(b) Calculate the work function (in eV) of sodium.

(2 mark)

The work function was the difference between the energy of the photon and the energy of the emitted electron.

$W = hf - E_K(max)$

$W = ((6.63 \times 10^{-34}) \times (1.00 \times 10^{15})) - (2.96 \times 10^{-19})$

$W = 3.67 \times 10^{-19}$ J

$\frac{3.67 \times 10^{-19} \text{ J}}{1.6 \times 10^{-19}} = \underline{2.29 \text{ eV}}$

(c) The intensity of the light is now reduced and the experiment is repeated. The students obtain a new graph of photocurrent against voltage. Sketch the new graph (*on the original graph above*).

(2 marks)

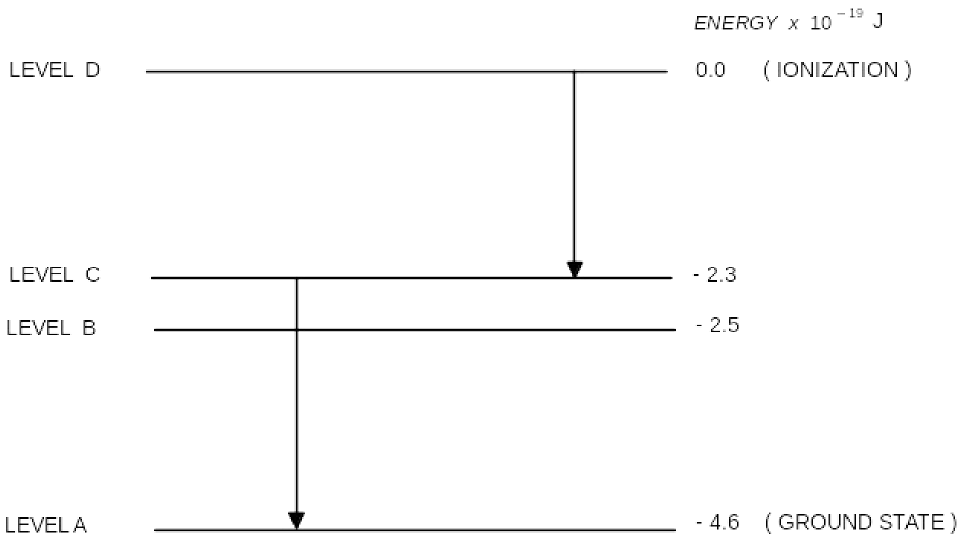
(d) The students change the light source to one with a different frequency. They observe that the photocurrent is zero and remains at zero regardless of the size or sign of the voltage. Explain this observation.

*The frequency of the incident photons was **less** than the **threshold** frequency and therefore the photons did not have enough energy to free any electrons.* ✓ *The energy of the photons was **less** than the **work** function.* ✓

(2 marks)

Question 11 (15 marks)

The diagram shows four energy levels of an atom not drawn to scale.



(a) Explain

*An elect ... rgy level by emitting photons with energies corresponding to the **change** in energy between the two energy levels. ($E = h$ x f).* ✓ *The frequency of the photon may correspond to the **frequency** of an electromagnetic radiation such as a colour in the visible spectrum.* ✓

(2 marks)

(b) Between which two levels is the longest wavelength of emitted radiation produced by a transition? Calculate the wavelength of this emitted radiation.

(3 marks)

As the frequency increases so the wavelength decreases. The longest wavelength will occur when the energy difference between levels is at its smallest.

i.e. C to B $= 0.2 \times 10^{-19}$ J . ✓

$E = h \times f$

$0.2 \times 10^{-19} = 6.64 \times 10^{-34} \times f$

$c = f \chi$

$3 \times 10^{8} = 3.01 \times 10^{13} \chi$

$= \dfrac{3 \times 10^{8}}{3.01 \times 10^{13}}$

The wavelength is $\underline{9.97 \times 10^{-6}\ m}$. ✓

$$f = \frac{0.2 \times 10^{-19}}{6.64 \times 10^{-34}}$$

$f = 3.01 \times 10^{13}$ Hz . ✓

(c) Draw **on the diagram** two vertical arrows between levels to indicate two different transitions that result in emitted radiation of the same frequency.

(2 marks)

(d) Describe the emission spectrum of this atom in terms of the number of lines and brightness.

There are 6 possible transitions. ✓
There will be 6 lines but two of the transitions have equal energy ✓
So one line will be brighter than the other five. ✓

(3 marks)

(e) How much energy, in eV, would be required to ionise the atom in its ground state?

(1 mark)

Energy required to ionise the atom is 4.6×10^{-19} J

$$\frac{4.6 \times 10^{-19}}{1.6 \times 10^{-19}} = \underline{2.87 \text{ eV}}$$

(f) In its ground state the atom is bombarded by a collision with an electron having 3.0×10^{-19}J of energy.

(i) With what possible energies could the electron be scattered from the atom after the collision?

(2 marks)

A to B $(3 \times 10^{-19}) - (2.1 \times 10^{-19}) = \underline{0.9 \times 10^{-19}}$ J ✓

A to C $(3 \times 10^{-19}) - (2.3 \times 10^{-19}) = \underline{0.7 \times 10^{-19}}$ J ✓

(ii) Calculate all the possible frequencies of radiation that the atom may subsequently emit, as a result of the bombardment.

(2 marks)

$2.1 \times 10^{-19} = (6.64 \times 10^{-34}) \times f$

$f = \underline{3.16 \times 10^{14}\ Hz}$ ✓

$2.3 \times 10^{-19} = (6.64 \times 10^{-34}) \times f$

$f = \underline{3.46 \times 10^{14}\ Hz}$ ✓

Question 10 (16 marks)

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) Estimate how far muons produced in the upper atmosphere might be expected to travel during an average lifetime of 2.2 μs.

(2 marks)

$s = v \times t$

$s = 0.98 \times (3 \times 10^{8}) \times (2.2 \times 10^{-6})$

$s = \underline{650\ m}$

(b) Significant numbers of muons produced in the upper atmosphere are detected at the Earth's surface. Briefly explain how this could occur.

*From the reference frame of the Earth, the muons are travelling at **near the speed of light** ✓ and so experience a significant **dilation** of their average lifetime ✓*

*Their extended lifetime enables considerable numbers of them to cross the width of the atmosphere and to **survive** until they reach the Earth's surface.*

(OR from the reference frame of the muons, the Earth is approaching at near the speed of light and so the distance to the Earth's surface experiences significant length contraction, enabling considerable numbers of muons to cover the shortened distance during their lifetime and reach the surface)

(3 marks)

(c) The pi meson, an unstable particle, lives on average about 2.6×10^{-8}s (measured in its own frame of reference) before decaying.

(i) If such a particle is moving with a speed of 0.8c, what lifetime is measured in the laboratory?

(2 marks)

$$t_v = \frac{t_0}{\sqrt{1-\left(\frac{v}{c}\right)^2}} = \frac{2.6 \times 10^{-8} s}{\sqrt{1-0.8^2}} = 4.333 \times 10^{-8} s$$

(ii) What distance, measured in the laboratory, does the particle move before decaying?

(2 marks)

$$v = \frac{l_0}{t_v}$$

$$l_0 = v \times t_v = 2.4 \times 10^8 m \cdot s^{-1} \times 4.333 \times 10^{-8} s$$

$$¿ 10.4 m$$

(iii) What distance, measured by an observer travelling with the meson, does the particle move before decaying?

(2 marks)

$$v = \frac{l_v}{t_0}$$

$$l_v = v \times t_0 = 2.4 \times 10^8 m \cdot s^{-1} \times 2.6 \times 10^{-8} s$$
$$¿ 6.24 m$$

(iv) How fast will an observer travelling with the meson compute its speed (show calculation)?

(2 marks)

$$¿ \frac{l_v}{t_0} = \frac{6.24 m}{2.6 \times 10^{-8} s} = 240000000 m \cdot s^{-1} = 0.8 c$$

(d) The occupants on a spacecraft travelling at 0.75c relative to the Earth measure the time interval between two events on Earth as being 37 hours. What time interval would they measure if they were instead travelling at a speed of 0.94c with respect to the Earth?

(3 marks)

$$t_0 = t_v^{0.75c} \times \sqrt{1 - \left(\frac{0.75 c}{c}\right)^2} = 37 \times \sqrt{1 - 0.75^2} = 24.473 hr$$

$$t_v^{0.94c} = \frac{t_0}{\sqrt{1 - \left(\frac{0.94 c}{c}\right)^2}} = \frac{24.473 hr}{\sqrt{1 - 0.94^2}} = 71.73 hr$$

Section C: Short Answers

Question 11 (13 marks)

Particle Physics – basic principles and techniques

Particle physics is the modern version of the age old quest – to find the smallest particles that cannot be broken down. Particle accelerators are the 'laboratory equipment' in this area of study. Charged particles can be accelerated in two senses – by their change of direction in circular paths or by increasing their speed. Studies can be made on the radiation that they emit whilst being accelerated or the after effects of collisions between high speed particles.

The **cyclotron** first came into use in 1928 using a combination of magnetic and electric fields to accelerate particles in a spiral path. Development of this technology led to the **synchrotron** which uses an evacuated circular tube with many magnets placed around its circumference. As particles are accelerated the electric field is adjusted and the strength of the magnets is increased to maintain a constant radius and compensate for relativistic effects that become important at high particle energies.

Any charged particle that accelerates will radiate electromagnetic energy. This is true even at a constant speed in a circular path. So a continual supply of energy is required in synchrotrons to just maintain a constant particle speed let alone increase their speed. The emitted radiation is known as **synchrotron radiation** and can cover the entire electromagnetic spectrum.

Linear accelerators (LINAC) use a straight path and a series of accelerating voltages as the particles move along the line. LINACs are often used to provide the early stages of acceleration before particles are fed into large synchrotrons.

Collider experiments take two beams of particles that have been separately accelerated in opposite directions and smash them into each other. This is difficult to achieve but if successful it is an efficient use of energy.

When two particles with an equal magnitude of momentum collide head on, the total momentum is zero before and after the collision. If particles are stationary after the collision, then their kinetic energy is zero. By the conservation of energy and mass principle, the energy before the collision is transformed into the mass of new particles formed in the collision. The particles that are present after a collision reaction can be different to those that went in. This is exactly what particle physicists aim to achieve and the discovery and study of these new particles underpins their work.

Every collision is governed by one of the **fundamental forces** (except the force of gravity which has no significant influence on such tiny particles in this context):

- The **electromagnetic force** leads to simple collisions between charged particles. No new particles are formed when this force is at work. e.g. $\boxed{p + p \rightarrow p + p}$
- The **strong force** dominates reactions between hadrons (which contain quarks). e.g. $\boxed{p + p \rightarrow p + n + \pi^0}$
- The **weak force** is likely to be involved in lepton reactions, especially if one of the leptons is a neutrino. e.g. $\boxed{\nu_e + \mu^- \rightarrow e^- + \nu_\mu}$

Einstein's theory of **special relativity** has led us to the idea that the mass of a moving object is not the same as its rest mass (m_0). The mass of a moving object cannot be measured directly; it must be calculated from a measurement of momentum and velocity. The relativistic equations for momentum ***p*** and total energy ***E*** are as follows:

$$\boxed{p = \frac{m_0 v}{\sqrt{1 - \frac{v^2}{c^2}}}} \qquad \boxed{E = \frac{m_0 c^2}{\sqrt{1 - \frac{v^2}{c^2}}}}$$

(These equations are only applicable for non-zero mass)

Relativity has also given us the idea of mass-energy equivalence. In Newton's version of mechanics, a lone particle not influenced by gravity or electromagnetism but moving at a given speed could only have a single form of energy – kinetic. At rest it had no energy at all. This is not the case in relativity.

The relationship is described by the equation: $\boxed{E^2 - p^2c^2 = m_0{}^2c^4}$

Photons are packets of energy travelling at the speed of light. Surprisingly it has been proved that although photons have zero mass they do have momentum. It can be shown for a photon that

if: $\boxed{E^2 - p^2c^2 = m_0{}^2c^4}$ then: $\boxed{p = \frac{E}{c}}$ and since $\boxed{E = hf}$ then: $\boxed{p = \frac{hf}{c} = \frac{h}{\lambda}}$

Particle physics has also proven to be vital in understanding the nature of the universe a few fractions of a second after the Big Bang. The conditions created in the mightiest accelerators are very similar to those that existed when the universe was 10^{-12} seconds old.

Questions

(a) In what sense can a particle be accelerated if its speed remains constant? Explain.

*Velocity has magnitude and **direction**.* ✓

*If a particle undergoes **circular** motion, a change in direction is also acceleration.* ✓

(2 marks)

(b) Once a charged particle has been accelerated to a given speed in a circular path, is further energy required to maintain a constant speed? Explain.

Yes it radiates synchrotron radiation ✓
so this energy must be replaced. ✓

(2 marks)

(c) Calculate the momentum of a **proton** travelling at 95% of the speed of light. The rest mass of a proton is given in the formula and constant sheet.

(3 marks)

$$p = \frac{m_0 v}{\sqrt{1 - \frac{v^2}{c^2}}} \qquad p = \frac{1.67 \times 10^{-27} \times 0.95 \times 3 \times 10^{8}}{\sqrt{1 - \frac{0.95^2}{1^2}}}$$

Substitutes correct values ✓
Correct handling of denominator ✓

Solves to $p = \underline{1.524 \times 10^{-18}}$ ✓ *(kg m s⁻¹)*

(Units desirable but not essential)

(d) The equation for Einstein's mass-energy equivalence is: $\boxed{E^2 - p^2c^2 = m_0{}^2c^4}$
Show that for a particle at rest this simplifies to $E = m_0 . c^2$

(2 marks)

If $v = 0$

then $p = \dfrac{m_0 v}{\sqrt{1 - \dfrac{v^2}{c^2}}}$ *equals zero (applicable as non-zero mass)* ✓

So $E^2 - p^2c^2 = m_0{}^2c^4$ *simplifies to* $E^2 = m_0{}^2.c^4$

By taking the square root on both sides then $E = m_0.c^2$ ✓

(e) From the starting point: $\boxed{E^2 - p^2c^2 = m_0{}^2c^4}$ show that the momentum of a **photon** with zero mass can be given by $\boxed{p = \dfrac{E}{c}}$

(2 marks)

If $E^2 - p^2c^2 = m_0{}^2c^4$ *and* $m_0 = 0$ *then* $E^2 - p^2c^2 = 0$ ✓

So $E^2 = p^2c^2$

$p^2 = E^2 / c^2$

Square root of both sides gives $p = \dfrac{E}{c}$ ✓

(A photon has zero mass so $p = \dfrac{m_0 v}{\sqrt{1 - \dfrac{v^2}{c^2}}}$ *does not apply to it.)*

(f) Calculate the momentum of a photon of 550 nm yellow light.

(2 marks)

Using the equation: $p = \dfrac{h}{\lambda}$, then $p = \dfrac{6.63 \times 10^{-34}}{550 \times 10^{-9}}$ ✓

p = $\underline{1.20545 \times 10^{-27}}$ *(kg m s^{-1})* ✓

(Units desirable but not essential)

END OF TEST