EXPLORING

# PHYSICS

YEAR 12 - EXPERIMENTS, INVESTIGATIONS & PROBLEMS

## Worked Solutions

The STAWA *Worked Solutions* have been developed through the collaboration of teachers working in Department of Education, Catholic Education WA and Association of Independent Schools of WA. Funding assistance was provided by the Department of Education.

The *Worked Solutions* are intended to support the problem sets of the STAWA ATAR Exploring Physics Year 12: experiments, investigations and problems.

In an endeavour to provide the highest quality publication, the STAWA *Worked Solutions* were written and checked by different teachers. This does not guarantee that all answers are correct. Teachers are advised to work through disputed solutions with their students. If they are sure there is an error then they are asked to forward corrections to STAWA by email: admin@stawa.net

The STAWA *Worked Solutions* are a great example of teachers helping teachers for the benefit of all students.

STAWA
SCIENCE TEACHERS' ASSOCIATION
OF WESTERN AUSTRALIA

YEAR
12
ATAR

# Revolutions in modern physics

The development of quantum theory and the theory of relativity fundamentally changed our understanding of how nature operates and led to the development of a wide range of new technologies, including technologies that revolutionised the storage, processing and communication of information.

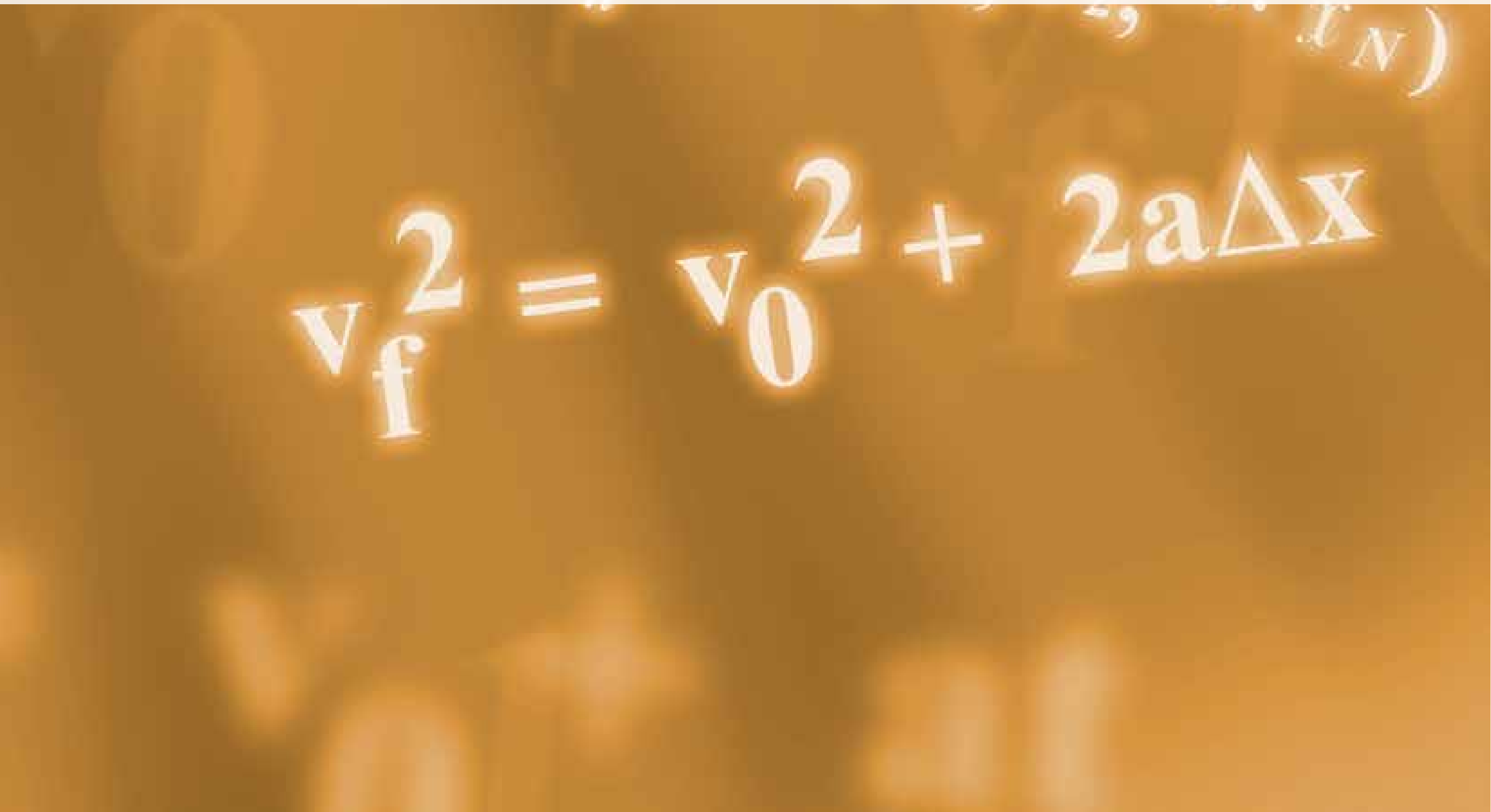
Develop your understanding of these modern theories by:

- Examining observations of relative motion, light and matter that could not be explained by existing theories.
- Investigating how the shortcomings of existing theories led to the development of the special theory of relativity and the quantum theory of light and matter.
- Evaluating the contribution of the quantum theory of light to the development of the quantum theory of the atom.
- Examining the Standard Model of particle physics and the Big Bang theory.

Explore modern physics through such contexts as black holes, dark matter, space travel and the digital revolution and technologies, such as photo radar, fibre optics, DVDs, GPS navigation, lasers, modern electric lighting, medical imaging, nanotechnology, semiconductors, quantum computers and particle accelerators, and astronomical telescopes such as the Square Kilometre Array.

Investigate and apply an understanding of relativity, black body radiation, wave/particle duality, and the quantum theory of the atom, to make and/or explain observations of a range of phenomena, such as atomic emission and absorption spectra, the photoelectric effect, lasers, and Earth's energy balance.

Continue to develop skills in planning, conducting and interpreting the results of investigations, in synthesising evidence to support conclusions, and in recognising and defining the realm of validity of physical theories and models.



## Problem Set 12.1: Waves and Photons

1. The comment that light can be transmitted as an electromagnetic wave refers to the face that light can be modelled by coupled transverse waves, one a magnetic field and the other an electrical field, at right angles to each other, that move forward by creating each from the other at the speed of light.

2. a) The term coherent is used to describe light sources of the same frequency, and that have a constant phase difference (ie they are in phase.).

   b) No – because they are producing more than one frequency of EM radiation. Coherent light must be monochromatic, as even if the light sources produced the same range of frequencies, there is no reason why both sources will produce the same frequency at the same time.

3. According to the formula $E = hf$ the energy of a photon is reliant not on the velocity of the photon, but on its frequency. Different colours of light correspond to photons of different frequencies, and therefore, according to $E = hf$, different energies.

4. $E = hf$
   $E = (6.63\times10^{-34})(3.85\times10^{14})$
   $E = 2.55\times10^{-19}$ J

5. $E = hf$
   $1.00\times10^{-17} = (6.63\times10^{-34})f$
   $f = 1.58\times10^{16}$ Hz

   This corresponds to the Ultraviolet region of the EM spectrum

6. a) $E = hf$
   $E = (6.63\times10^{-34})(1.30\times10^{6})$
   $E = 8.62\times10^{-28}$ J

   b) $c = \lambda f$
   $\lambda = \frac{3.00\times10^{8}}{1.30\times10^{6}}$
   $\lambda = 2.31\times10^{2}$ m

   c) $E = \frac{1}{2}\,m\,v^{2}$
   $8.62\times10^{-28} = \frac{1}{2}(9.11\times10^{-31})v^{2}$
   $v = 4.35\times10^{1}$ $\text{ms}^{-1}$

7. a) $c = \lambda f$
   $\lambda = \frac{3.00\times10^{8}}{2650\times10^{6}}$
   $\lambda = 1.13\times10^{-1}$m

   b) $E = hf$
   $E = (6.63\times10^{-34})(2650\times10^{6})$
   $E = 1.76\times10^{-24}$ J

c) Energy after 2.5 mins:

$E_{tot} = P.t$

$E_{tot} = 1100 \times 2.5 \times 60$

$E_{tot} = 165000$ J

$n_{photon} = \frac{E_{tot}}{E_{photon}}$

$n_{photon} = \frac{165000}{1.76 \times 10^{-24}}$

$n_{photon} = 9.38 \times 10^{27}$ photons

8. a) UV

b) $E = hf$

$E = \frac{hc}{\lambda}$

$E = \frac{(6.63 \times 10^{-34})(3.00 \times 10^{8})}{905 \times 10^{-9}}$

$E = 2.20 \times 10^{-19}$ J

c) $E_{pulse} = P.t$

$E = 34(150 \times 10^{-9})$

$E = 5.1 \times 10^{-6}$ J

$n_{photons} = \frac{E_{pulse}}{E_{photon}}$

$n_{photon} = \frac{5.1 \times 10^{-6}}{2.20 \times 10^{-19}}$

$n_{photon} = 2.32 \times 10^{13}$ photons

9. Antennas need to be mounted in an orientation which corresponds to the method of polarisation the waves they're receiving have been subject to. Horizontal antennas are placed to receive TV signals, as the TV signals are horizontally polarised themselves.

10. a) $c = \lambda f$

$\lambda = \frac{3.00 \times 10^{8}}{1.52 \times 10^{9}}$

$\lambda = 1.97 \times 10^{-1}$ m

b) $E = hf$

$E = (6.63 \times 10^{-34})(1.52 \times 10^{9})$

$E = 1.01 \times 10^{-24}$ J

c) $n_{photons\ in\ 1\ second} = \frac{E_{energy\ released\ in\ 1\ second}}{E_{photon}}$

$n_{photons\ in\ 1\ second} = \frac{5.00}{1.01 \times 10^{-24}}$

$n_{photons\ in\ 1\ second} = 4.95 \times 10^{24}$ photons in 1 second

d) Assuming time elapsed starts with the first pulse:

250 pulses in 1 second.

$$E_{single\ pulse} = \frac{E_{1\ second}}{E\ pulses\ in\ 1\ second}$$
$$E_{single\ pulse} = \frac{5.00}{250}$$
$$E_{single\ pulse} = 2.00\times10^{-2}\text{J}$$

11. $c = \lambda f$

$$f = \frac{3.00\times10^{8}}{435\times10^{-9}}$$
$$f = 6.90\times10^{14}\text{Hz}$$

$$E = hf$$
$$E = (6.63\times10^{-34})(6.90\times10^{14})$$
$$E = 4.57\times10^{-19}\text{J}$$

$$P = E_{photon} \cdot n_{photons\ in\ 1\ second}$$
$$P = 4.57\times10^{-19}.\,3.25\times10^{18}$$
$$P = 1.49\text{W}$$

$$W = P.t$$
$$W = 1.49\times1.2\times10^{-3}$$
$$W = 1.78\times10^{-3}\text{J}$$

12. a) $E = hf$

$$E = \frac{hc}{\lambda}$$
$$E = \frac{(6.63\times10^{-34})(3.00\times10^{8})}{694\times10^{-9}}$$
$$E = 2.87\times10^{-19}\ \text{J}$$

b) $I = \frac{P}{A}$

$$I = \frac{1.00}{10\times10^{-6}}$$
$$I = 100000\ \text{W.m}^{-2}$$

c) Laser is 100x brighter.

13. $E = hf$

$$E = \frac{hc}{\lambda}$$
$$E = \frac{(6.63\times10^{-34})(3.00\times10^{8})}{6.00\times10^{-7}}$$
$$E = 3.32\times10^{-19}\ \text{J}$$

$$n_{photons\ in\ 1\ second} = \frac{E_{energy\ released\ in\ 1\ second}}{E_{photon}}$$
$$n_{photons\ in\ 1\ second} = \frac{1.70\times10^{-8}}{3.32\times10^{-19}}$$
$$n_{photons\ in\ 1\ second} = 5.13\times10^{10}\ \text{photons in 1 second}$$

14. a) $c = \lambda f$

$$\lambda = \frac{3.00\times10^{8}}{720\times10^{3}}$$

$$\lambda = 4.17\times10^{2}\text{m}$$

b) Assuming the full power is used for the day:

$$E = P.t$$

$$E = 50\times10^{3}\times60\times60\times24$$

$$E = 4.32\times10^{9}\text{J}$$

15. a) $E = hf$

$$f = \frac{E}{h}$$

$$f = \frac{2.00\times10^{-24}}{6.63\times10^{-34}}$$

$$f = 3.02\times10^{9}\ \text{Hz}$$

b) $c = \lambda f$

$$\lambda = \frac{3.00\times10^{8}}{3.02\times10^{9}}$$

$$\lambda = 9.95\times10^{-2}\text{m}$$

c)

| | Compared to VL |
|---|---|
| $E$ | Smaller |
| $f$ | Lower |
| $\lambda$ | Greater |

16. a) Green light has a higher frequency than the IR beam, which means it is less likely to interact with the molecules on the way through the water.

b) High intensity means the beam consists of many photons. It needs a high intensity because photons may scatter due to collisions with molecules in the water. The more photons, the more photons that will successfully be reflected back.

c) Wavelength = $.75\times532 = 399$ nm

d) Frequency doesn't change between different media

$$f = \frac{c}{\lambda}$$

$$f = \frac{3\times10^{8}}{532\times10^{-9}}$$

$$f = 5.64\times10^{14}\ \text{Hz}$$

e) Speed of light in water is roughly 75% of the speed of light in air.

$$speed = \frac{distance}{time\ from\ bottom\ of\ ocean\ to\ top}$$

$$0.75\times3\times10^{8} = \frac{distance}{\frac{1}{2}(3.8\times10^{-6})}$$

$$distance = 427.5\ \text{m}$$

17. a) Incandescent globes only emit a small proportion of energy supplied as visible light. A large proportion of the energy supplied is radiated as heat; EM radiation in the Infrared range.

b) Blackbody curve should have its peak in the UV part of the spectrum.

c) $c = \lambda f$

$$\lambda = \frac{3.00\times10^{8}}{5.28\times10^{16}}$$

$$\lambda = 5.68\times10^{-9}\ \text{m}$$

d) $E = hf$

$$E = (6.63\times10^{-34})(5.28\times10^{16})$$

$$E = 3.50\times10^{-17}\,\text{J}$$

$$E = 2.19\times10^{2}\ \text{eV}$$

e) $$n_{photons\ in\ 1\ second} = \frac{E_{energy\ released\ in\ 1\ second}}{E_{photon}}$$

$$n_{photons\ in\ 1\ second} = \frac{75.0}{3.50\times10^{-17}}$$

$$n_{photons\ in\ 1\ second} = 2.14\times10^{18}\ \text{photons in 1 second}$$

f) It would be hard to determine the number of photons from experimental measure, as the photons are not travelling in a beam towards a detector like in a laser, but radially. This is impractical to detect due to the fact they can travel in any direction.

## Problem Set 12.2: The photoelectric effect

1. The photoelectric effect supported the particle model of light in two significant ways. Firstly, the fact there was a threshold frequency which determined whether or not a photoelectron current would flow supported the idea that each quantum of light contains a certain amount of energy; dependant on the frequency of that light. Secondly, the effect of increasing the intensity of the light on the photoelectron current when the light source is above the threshold frequency also supports the idea that the number of photons is related to the intensity.

2. $E = \frac{hc}{\lambda}$
   $h = \frac{E\lambda}{c}$
   $h = \frac{4.00\times10^{-7}\times1.40\times10^{-19}}{3\times10^{8}}$
   $h = 1.87\times10^{-34}\text{J.s}$

   $h = \frac{3.00\times10^{-7}\times3.06\times10^{-19}}{3\times10^{8}}$
   $h = 3.06\times10^{-34}\text{J.s}$

3. $E_K = hf - W$
   $E_K = 6.63\times10^{-34}\times6.7\times10^{14} - 2.14\times1.60\times10^{-19}$
   $E_K = 1.02\times10^{-19}$ J

4. a) The minimum energy required of a photon incident on the metal surface to liberate an electron.

   b) $E = \frac{hc}{\lambda}$
   $\lambda = \frac{hc}{E}$
   $\lambda = \frac{6.63\times10^{-34}\times3\times10^{8}}{4.08\times1.60\times10^{-19}}$
   $\lambda = 3.04\times10^{-7}\text{m}$

   c) $E_K = hf - W$
   $E_K = 6.63\times10^{-34}\times2.3\times10^{15} - 4.08\times1.60\times10^{-19}$
   $E_K = 9.32\times10^{-19}$ J

5. a) No effect

   b) No effect

   c) No effect

   d) Different metals have different work functions, which mean there are differences in the minimum frequency of light that will cause photoelectrons to be emitted from the metal (the threshold frequency).

   e) According to $= \frac{c}{f}$ , the wavelength and frequency are inversely proportional. Increasing the wavelength will cause a decrease in the frequency of the light. If this drops below the threshold frequency, no photoelectrons will be emitted.

f) If the frequency is above the threshold frequency, a higher intensity will increase the photoelectron current. If the frequency is below the threshold frequency, no current will flow, and changing the intensity will not change this.

g) If the surface of the metal is covered (and the material is opaque) light will not be able to strike the surface of the metal. If this is the case, the photoelectric effect will not be seen.

6. a) $E_{photon} = \frac{hc}{\lambda}$

$E_{photon} = \frac{6.63\times10^{-34}\times3\times10^{8}}{325\times10^{-9}}$

$E_{photon} = 6.12\times10^{-19}\text{J}$

$E_{photon} = 3.83\text{ eV}$

$E_K = E_{photon} - W$

$E_K = 3.83 - 5.01$

No solution as the incident energy is below the work function.

b) No effect. The stopping potential is related to the maximum kinetic energy of the electrons that are liberated. Doubling the intensity changes the amount of photoelectrons which are liberated, but not the energy of those electrons (this is related to increasing the frequency of the light). Therefore, there is no effect on the stopping potential.

7. a) At the threshold frequency, electrons are free but have no kinetic energy.

$E_K = hf - W$

$0 = hf - W$

$W = 1.25\times10^{14}\times6.63\times10^{-34}$

$W = 8.29\times10^{-20}\text{J}$

$W = 5.18\times10^{-1}\text{eV}$

b) $\lambda = \frac{c}{f}$

$\lambda = \frac{3.00\times10^{8}}{6.95\times10^{14}}$

$\lambda = 4.31\times10^{-7}\text{m}$

c) $E = hf$

$E = 6.63\times10^{-34}\times6.95\times10^{14}$

$E = 4.61\times10^{-19}\text{J}$

$E = 2.88\text{ eV}$

d) $E_K = hf - W$

$E_K = 2.88 - 5.18\times10^{-1}$

$E_K = 2.36\text{ eV}$

e) $E_K = 2.36\text{eV} = 3.78\times10^{-19}\text{J}$

$$E_K = \frac{1}{2}mv^2$$

$$3.78\times10^{-19} = \frac{1}{2}(9.11\times10^{-31})v^2$$

$$v = 9.11\times10^5\text{m.s}^{-1}$$

8. a) $E_{photon} = \frac{hc}{\lambda}$

$$E_{photon} = \frac{6.63\times10^{-34}\times3\times10^8}{287\times10^{-9}}$$

$$E_{photon} = 6.93\times10^{-19}\text{J}$$

$$E_{photon} = 4.33\text{ eV}$$

$$E_{K\,MAX} = 3.68\text{ eV}$$

$$E_K = E_{photon} - W$$

$$3.68 = 4.33 - W$$

$$W = 6.51\times10^{-1}\text{eV}$$

b) $E_{K\,MAX} = 3.68\text{ eV} = 5.89\times10^{-19}\text{J}$

$$E_{K\,MAX} = \frac{1}{2}mv^2$$

$$5.89\times10^{-19} = \frac{1}{2}(9.11\times10^{-31})v^2$$

$$v = 1.14\times10^6\text{m.s}^{-1}$$

9. a) In order for photoelectrons to be emitted from the surface the photons must have a minimum energy to dislodge them. As E=hf, this corresponds to photons of a minimum frequency. This is different for each material, however. 465nm light must correspond to a frequency which is higher than the threshold frequency in sodium, but not in platinum.

b) The current will increase in sodium as a higher intensity will mean more photons are produced, meaning more electrons will be liberated. As the light is below the threshold frequency for platinum, platinum’s current will remain at zero.

c) $\lambda \, \alpha \frac{1}{f}$ : increasing wavelength greatly greatly deceases frequency. Sodium will most likely stop producing electrons as a great decrease to frequency would put it below the threshold frequency, and platinum’s current will remain at zero.

d) $\lambda \, \alpha \frac{1}{f}$ : decreasing wavelength greatly increases frequency. Sodium will continue producing electrons at the same rate, and platinum is likely to produce a photoelectron current as a great increase to its frequency will most likely bring it above the threshold frequency.

e) Current will decrease in sodium, as a small reverse voltage will stop electrons with lower kinetic energy from moving.

10. a) $f = \frac{c}{\lambda}$

$f = \frac{3.00\times10^{8}}{3.55\times10^{-7}}$

$f = 8.45\times10^{14}$ Hz

b) $E = hf$

$E = 6.63\times10^{-34}\times8.45\times10^{14}$

$E = 5.60\times10^{-19}$J

c) $E_K = E_{photon} - W$

$E_K = 5.60\times10^{-19} - 2.64\times10^{-19}$

$E_K = 2.96\times10^{-19}$J

d) $W = \frac{hc}{\lambda}$

$2.64\times10^{-19} = \frac{6.63\times10^{-34}\times3.00\times10^{8}}{\lambda}$

$\lambda = 7.53\times10^{-7}$ m

11. There is no energy change, but there will be a decrease in the number of photoelectrons (a decrease in the current). The light source does not change in frequency so the energy of the photons is constant throughout the entire process. The smoke, however, would cause photon to deflect from their path towards the photocell. This means less photons would interact with the electrons on the surface of the photocell, causing less photoelectrons to be emitted. This means the current would decrease.

12. bi) $f_0 = 9.00\times10^{14}$ Hz (x-intercept of graph)

ii) $h = 6.36\times10^{-34}$J.s ( gradient of graph)

iii) $W = 5.71\times10^{-19}$J (y-intercept of graph)

## Problem Set 13: Quantum Theory

1. a) These dark lines are absorption lines. When light travels through the elements and compounds in stars, photons of certain wavelengths are absorbed. The light from the star when viewed on Earth, therefore, is missing certain wavelengths. This causes the dark lines in the spectrum.

   b) Every absorption spectral line is also present in the emission spectra lines for a given element. By looking at the emission spectra for different elements in the lab we can account for all the lines, which are present in the absorption spectra of a star, and hence deduce which elements are in the star.

   c) The substance must be at a high temperature.

2. a) When white light is shone through the solution the molecules absorb certain frequencies of light. As white light contains all colours of light, the green colour is what we perceive to be the combination of all colours in white light without the colours which were absorbed.

   b) Absorption spectra.

3. a) $\Delta E = \frac{hc}{\lambda}$

   $\Delta E = \frac{6.63\times10^{-34}\times3\times10^{8}}{557.7\times10^{-9}}$

   $\Delta E = 3.57\times10^{-19}\text{J}$

   $\Delta E = 2.23 \text{ eV}$

   b)

**4. (i) E2 to E1**

(a) $\Delta E = 10.2\ eV$

$\Delta E = 1.63\times10^{-18}\text{J}$

$\Delta E = hf$

$f = \frac{1.63\times10^{-18}}{6.63\times10^{-34}}$

$f = 2.46\times10^{15}\text{Hz}$

(b) Ultraviolet

**(ii) E4 to E2**

(a) $\Delta E = 2.55eV$

$\Delta E = 4.08\times10^{-19}\text{J}$

$\Delta E = hf$

$f = \frac{4.08\times10^{-19}}{6.63\times10^{-34}}$

$f = 6.15\times10^{14}\text{Hz}$

(b) Visible

**(iii) E3 to E2**

(a) $\Delta E = 1.89eV$

$\Delta E = 3.02\times10^{-19}\text{J}$

$\Delta E = hf$

$f = \frac{3.02\times10^{-19}}{6.63\times10^{-34}}$

$f = 4.56\times10^{14}\text{Hz}$

(b) Visible

**(iv) E5 to E3**

(a) $\Delta E = 0.97eV$

$\Delta E = 1.55\times10^{-19}\text{J}$

$\Delta E = hf$

$f = \frac{1.55\times10^{-19}}{6.63\times10^{-34}}$

$f = 2.34\times10^{14}\text{Hz}$

(b) Infrared

(c) $\Delta E = \frac{hc}{\lambda}$

$\Delta E = \dfrac{6.63\times10^{-34}\times3\times10^{8}}{434\times10^{-9}}$

$\Delta E = 4.58\times10^{-19}\text{J}$

$\Delta E = 2.86 \text{ eV}$

$E_5 \rightarrow E_2$ gives this difference.

5. $\Delta E = hf$

$\Delta E = 6.63\times10^{-34}\times4.00\times10^{14}$

$\Delta E = 2.65\times10^{-19}\text{J}$

$\Delta E = 1.66 \text{ eV}$

$\text{E}_{higher} = 1.66 + E_{lower}$

$\text{E}_{higher} = 4.01\text{eV}$

6. Absorption spectra results when an electron in the ground state gains energy and transitions to a higher energy level. Emission spectra is the result of electrons moving from a higher energy level to a lower one; including all transitions to the ground state. Therefore any absorption spectra line will be present in the emission spectra.

7. a) 2.80 eV (no collisions), 1.42 eV (hits ground state goes to 1st), 0.5 eV (hits ground state goes to 2nd)

b) 1.38 eV (E2→E1), 2.30 eV (E3→E1), 0.92 eV (E3→E2)

c) Energies greater than or equal to 13.87 eV

d) The beam would be missing photons of energy 1.38 eV, 2.30 eV, and any photons of energy between 13.87 eV and 14.5 eV (inclusive).

8. (a) 2.06 eV

(b) $E = \frac{hc}{\lambda}$

$2.06\times1.60\times10^{-19} = \frac{6.63\times10^{-34}\times3\times10^{8}}{\lambda}$

$\lambda = 6.03\times10^{-7}\text{m}$

(c) $\frac{E\lambda}{c} = h$

$h = \frac{2.06\times1.60\times10^{-19}\times600\times10^{-9}}{3\times10^{8}}$

$h = 6.59\times10^{-34} J.s$

9. $\Delta E = \frac{hc}{\lambda}$

$$\Delta E = \frac{6.63\times10^{-34}\times3\times10^{8}}{656.3\times10^{-9}}$$
$$\Delta E = 3.03\times10^{-19}\text{J}$$
$$\Delta E = 1.89 \text{ eV}$$

10. $\Delta E = \frac{hc}{\lambda}$

$$\Delta E = \frac{6.63\times10^{-34}\times3\times10^{8}}{5.84\times10^{-8}}$$
$$\Delta E = 3.41\times10^{-18}\text{J}$$
$$\Delta E = 2.13\times10^{1} \text{ eV}$$

11. $E = \frac{hc}{\lambda}$

$$E = \frac{6.63\times10^{-34}\times3\times10^{8}}{\lambda} \text{ J}$$
$$E = \frac{1.99\times10^{-25}}{\lambda} \text{ J}$$
$$E = \frac{1.99\times10^{-25}}{\lambda(1.6\times10^{-19})} \text{ eV}$$
$$E = \frac{1.24\times10^{-6}}{\lambda} \text{ eV}$$

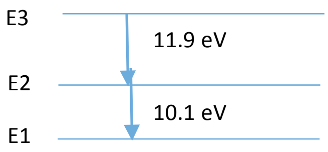
12. (a) $E_1 = \frac{hc}{\lambda}$

$$E_1 = \frac{6.63\times10^{-34}\times3\times10^{8}}{1.042\times10^{-7}}$$
$$E_1 = 1.91\times10^{-18} \text{ J} = 11.9 \text{ eV}$$

$$E_2 = \frac{hc}{\lambda}(1.6 * 10$$
$$E_2 = \frac{6.63\times10^{-34}\times3\times10^{8}}{1.235\times10^{-7}}$$
$$E_2 = 1.61\times10^{-18} \text{ J} = 10.1 \text{ eV}$$

$$\lambda = \frac{hc}{E_1+E_2}$$
$$\lambda = \frac{6.63\times10^{-34}\times3\times10^{8}}{3.52\times10^{-18}}$$
$$\lambda = 5.65\times10^{-8}\text{m}$$

(b)



13. (a) 21.2 eV = 3.39 x $10^{-18}$ J photons.

$$E = hf$$
$$3.339\times10^{-18} = 6.63\times10^{-34}f$$
$$f = 5.12\times10^{15}\text{Hz}$$

UV

b) There would still be the same emission spectra, as electrons can give a portion of their kinetic energy after a collision. We should expect to see ionised helium, however.

c) The transmitted beam would be missing photons of energy 21.2eV, and anything equal to or above 24.6 eV. There is no change to the maximum photon which can be emitted, as there is still only one transition downwards, from the 21.2 eV energy level to the ground state.

# Problem Set 14.1: Special relativity explanation questions

1. (a) An inertial reference frame is a region of space which has no net force acting on it – it is not accelerating as would be detected by an accelerometer. In inertial frames velocity is constant
   (b) Not necessarily - they are both inertial frames but not the same frame. Measurements in one inertial frame can be converted to measurements in another by a simple transformation.

2. The laws of physics are the same in all inertial reference frames.
   The speed of light in a vacuum is absolute and has the same value in all inertial reference frames.

3. "Proper" time is the time between two simultaneous events as seen and measured by an observer who is stationary relative to the object on which measurements are being made

4. Light is subject to Special Relativity, which says that anything with zero rest mass must travel through space-time at the speed of light. Light has zero rest mass and therefore, according to Special Relativity, must always travel through space-time at the speed of light. A photon has no experience of the passage of time so is everywhere at once.

5. The equation $E = mc^2$ applies only to particles with rest mass. A photon has energy and momentum but no rest mass and must travel at the speed of light. It has an energy proportional to its frequency but no minimum energy and if it stops moving it ceases to exist.

6. Having different velocities means they must be in different frames of reference. This includes having the same speed but moving in different directions or having different speeds in the same direction. In both of these cases there will be an acceleration because a change in velocity exists. According to special relativity if a frame is non-inertial it must be undergoing an acceleration and therefore not have a constant velocity. Two non-inertial frames will also be accelerating with respect to each other, unless they are accelerating in exactly the same way and in the same direction.

7. Velocities don't add up like they do in Newtonian mechanics. The relativity of space and time extends to velocity. The two velocities can be added together and the relative velocity for this data will be $(0.70+0.70)c/(1+0.70 \times 0.70) = 1.4c/1.49 = 0.94c$.

8. The Lorentz contraction is not significant for an aircraft flying at a speed well below the velocity of light so there are no design issues to consider.
   It is not necessary to worry about Lorentz contraction in any ship design, regardless of speed, because such contraction is relative and measured from a frame external to that of the ship. In the ship's own frame it has its proper length.

9. Density is mass per unit volume. Relativistic speed will result in a relativistic mass increase and a relativistic length decrease, therefore a relativistic increase in density.

10. When viewed in the reference frame of the starship the distance between the Earth and Alpha Centauri is seen as being length contracted and the clock as running normally.
    To the Earth-based observer the spaceship clock is seen as being time dilated by the same factor but the distance is unchanged.
    Observers in both locations agree the journey time is the same relative to their own frames of reference but their reasons are quite different –one being due to time dilation and the second to length contraction.

11. The relativistic mass of an object clearly increases as velocity increases. The length also decrease as at relativistic speeds. If length contracts then volume must decrease and as density = mass/volume, an increase in mass and a decrease in volume must result in an increase in density.

12. a) Length and time contract making c = Dx/Dt constant

    b) An observer outside would see that the spaceship would have changed its shape, being shorter in the direction of travel. However, in the spaceship's frame, everything has its proper length.

13. To a photon of light distance and time do not exist – so light is in effect subject to the effects mentioned

14. Light within a prism or some other medium appears to travel slower – this is due to the interaction of the electro-magnetic wave with electric and magnetic fields within the material.

15. $L = L_0 \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} = 2.2 \times \frac{1}{\sqrt{1-0.49}} = 3.1km$

16. According to you (in the spaceship), your clock runs exactly the same as it did when you were at rest on Earth, all objects in your ship appear the same to you as they did before, and the speed of light is still c. There is nothing you can do to find out if you are actually moving.

17. The speed of light is the same in all reference frames, independent of the speed of the source or the observer. Therefore, the light still travels at the speed c, and what you see in the mirror will be exactly the same as what you would see if you were at rest.

18. The scientist will observe the light beam reaching him at speed = c. Because of the principle of the constancy of the velocity of light, each observer will measure the light beam from the headlight as traveling at the same speed. This may be contrary to what you expected as you might have thought that the observer in oncoming spaceship would have measured the beam moving at (the speed of light) + (2 x the speed of the spaceship). Nevertheless, this is not what is observed in practice. What is actually occurs in the real world is that no one ever measures light moving faster or slower than c.

## Problem Set 14.2: Special Relativity Calculations

1. $t = 2t_0$

$t = \gamma t_0$

$\therefore \gamma = 2$

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

$1-\frac{v^2}{c^2} = \frac{1}{4}$

$\frac{v^2}{c^2} = \frac{3}{4} = 0.75$

$v^2 = 0.75\ (3 \text{ x } 10^8)^2$

$v = \sqrt{0.75(3\text{x}10^8)^2}$

$= 2.60 \text{ x } 10^8 \text{ ms}^{-1}$

2. $l\ = 0.7\ l_0$

$l\ = \frac{l_0}{\gamma}$

$\therefore \gamma = \frac{1}{0.7}$

$\therefore \sqrt{1-\frac{v^2}{c^2}} = 0.7$

$1-\frac{v^2}{c^2} = (0.7)^2$

$1-\frac{v^2}{c^2} = 0.49$

$\frac{v^2}{c^2} = 0.51$

$v^2 = 0.51\ (3 \text{ x } 10^8)^2$

$v = \sqrt{0.51\ (3\text{x}10^8)^2}$

$v = 2.14 \text{ x } 10^8 \text{ ms}^{-1}$

3. $m_o = 2.5$ t

$V = 0.92c$

$p = \gamma mv$

$p = \frac{mv}{\sqrt{1-\frac{v^2}{c^2}}}$

$= \frac{2.5\text{x}10^3 \text{ x } 0.92(3\text{x}10^8)}{\sqrt{1-0.9^2}}$

$= \frac{6.75 \text{ x } 10^{11}}{\sqrt{0.19}}$

$= 1.55 \text{ x } 10^{12} \text{ kgms}^{-1}$

4. $u' = 0.8c$

$u = \frac{v-u'}{1+\frac{vu'}{c^2}}$

$= \frac{(0.8+0.8)c}{1+0.64}$

$= \frac{1.6c}{1.64}$

$= 0.975c$

5. $t = 1$s

$v = 0.92c$

$t = \gamma$ t0

$t_0 = \frac{t}{\gamma}$

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

$= \frac{1}{\sqrt{1-0.92^2}}$

$= 2.55$ s

6. $l_0 = 200 \text{ m}$

$l = 160 \text{ m}$

$$l = \frac{l_0}{\gamma}$$

$$l = l_0\sqrt{1-\frac{v^2}{c^2}}$$

$$(\frac{l}{l_0})^2 = 1-\frac{v^2}{c^2}$$

$$(\frac{160^2}{200^2}) = 1-\frac{v^2}{c^2}$$

$$\frac{v^2}{c^2} = 1-0.8^2$$

$$v^2 = 0.36c^2$$

v=0.6c

7a. v=0.995c

$l_0 = 250 \text{ light years}$

$$l = \frac{l_0}{\gamma}$$

$$l = l_0\sqrt{1-\frac{v^2}{c^2}}$$

$$= 250\sqrt{1-0.995^2}$$

= 24.97 yr

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

$$= \frac{24.97}{0.995}\text{yr}$$

= 25.1 yr

7b v=0.995v

$l$ =250 light year

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

8. v=0.994c

$l_0 = 250 \text{ light years}$

t=3.00 x $10^{-8}$ s

$$l = \upsilon_0 t$$

=0.994 x 3.00 x $10^{8}$ x 3.00 x $10^{-8}$

=8.946 m

$$l = l_0\sqrt{1-\frac{v^2}{c^2}}$$

$$l = l_0\sqrt{1-\frac{v^2}{c^2}}$$

$$8.946 = l_0\sqrt{1-0.992^2}$$

$$l_0 = \frac{8.946}{0.1094}$$

=81.8 m

∴ hanger length 81.8 m

9. $t_{\frac{1}{2}}(\mu) = 26 \ \mu\text{s}$

$$\upsilon_0 = 0.95c$$

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

$$= \frac{26\text{x}10^{-6}}{\sqrt{1-0.95^2}}$$

= 8.33 x $10^{-5}$ s

10. $\upsilon_E = 0.70c$

$\upsilon_D = 0.85c$

a. Earth observer would see them as 0.7c + 0.85c

b. Discovery would see Earth as moving away at 0.85c

c. Wrong because the speed of light is absolute.

$$u' = \frac{u+v}{1-\frac{uv}{c^2}}$$

$$= \frac{(0.85+0.70)c}{1+0.85\text{x}0.7}$$

$$= = \frac{1.55}{1.615}c$$

=0.960c

11. $l = 1.2 \text{ x } 10^5$ light year

$\upsilon_0 = 0.98c$

$$l = l_0\sqrt{1-\frac{v^2}{c^2}}$$

$$= 1.2 \text{ x } 10^5\sqrt{1\text{-}0.98^2}$$

= 2.39 x $10^4$ light years

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

$$= \frac{1.2 \text{ x } 10^5}{0.98}$$

=1.22 x $10^5$ Yr

12. v=0.95c

$t_0 = 3$ hours

Start 0900

Finish 1200

He would observe 1200 on his clock because time is only dilated relative to the Earth observer

13. $l_0 = 600$ m

$\upsilon_0 = 0.80c$

a. they are both inertial frames provided they are moving at a constnt velocity.

b. $t = \frac{s}{v} = \frac{600}{3\text{x}10^8}$

= 2.00 x $10^{-6}$ s

c. distance laser travels = length of fighter as seen from mothership plus distance spaceship travels in that time

$$c\Delta t = \gamma l_0 + \upsilon\Delta t$$

$$\Delta t = \frac{\gamma l_0}{c-\upsilon} = \frac{600\sqrt{1-0.64^2}}{c-0.8c}$$

$$= \frac{461.0}{0.2 \text{ x } 3\text{x}10^8}$$

= 6 x $10^6$ s

14.

15. $\upsilon_p = 3.5 \text{ x } 330 \text{ ms}^{-1}$= 1155 $\text{ms}^{-1}$

$\upsilon_m = 700 \text{ ms}^{-1}$

a. $\upsilon_{missile} = 1155 + 700 = 1855 \text{ ms}^{-1}$

b. $u = \frac{v-u'}{1+\frac{vu'}{c^2}}$

$$= \frac{1855}{1+\frac{1155\text{x}700}{(3\text{x}10^8)^2}}$$

$$= \frac{1855}{:\ 1}$$

=1855 $\text{ms}^{-1}$

The same because not relativistic

16. $\upsilon = 0.25c$

$u' = 0.65\ c$

$$u = \frac{v + u'}{1 + \frac{vu'}{c^2}}$$

$$= \frac{0.90c}{1 + 0.25x0.65}$$

$$= \frac{0.9c}{1.625}$$

$=0.554c\ ms^{-1}$

17. $m_0 = 3400\ kg$

$\upsilon = 2.25x10^8\ ms^{-1}$

$m = \gamma m_0$

$$m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$= \frac{3400}{\sqrt{1 - (\frac{2.25x10^8}{3x10^8})^2}}$$

$$= \frac{3400}{0.6614}$$

$=5.14\ x\ 10^3\ kg$

18. $l_0 = 158\ m$

$\upsilon = 0.925c$

$m_o = 8.00\ x\ 10^5\ kg$

$$m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$= \frac{8.00x10^5}{\sqrt{1 - 0.925^2}}$$

$= 2.11\ x\ 10^8\ kg$

$$l = l_0\sqrt{1 - \frac{v^2}{c^2}}$$

$$= 158\sqrt{1 - 0.925^2}$$

$= 60\ m$

19. $m=3m_o$

$m = \gamma m_0$

$$m_0 = \frac{m}{\gamma}$$

$$m_0 = 3m_0\sqrt{1 - \frac{\upsilon^2}{c^2}}$$

$$\sqrt{1 - \frac{\upsilon^2}{c^2}} = \frac{1}{3}$$

$$1 - \frac{v^2}{c^2} = \frac{1}{9}$$

$$\frac{\upsilon^2}{c^2} = \frac{8}{9}$$

$$\upsilon^2 = \frac{8}{9}c^2$$

$\upsilon = 0.943c$

## Problem Set 15.1: The standard model

1. The hundreds of known particles are all made from: 6 quarks, 6 leptons, 6 antiquarks, 6 antileptons, and the force carriers.

2. Neutrons and protons are made up of quarks, which are held together by gluons
Electrons are fundamental particles and are classified as leptons.

3. Baryons and mesons are hadrons.

   BARYONS - are any hadron made of three quarks (qqq). Protons and neutrons are baryons because they are each made of three quarks – protons two up and one down quark (uud) and neutrons one up and two down (udd).

   MESONS are hadrons made from a quark and its anti-quark (eg pion or pi-meson). One example of a meson is a pion (+), which is made of an up quark and a down anitiquark. The antiparticle of a meson just has its quark and antiquark switched, so an antipion (-) is made of a down quark and an up antiquark. Because a meson consists of a particle and an antiparticle, it is very unstable. The K meson lives much longer than most mesons, which is why it was called "strange" and gave this name to the strange quark, one of its components.

4. Both muon and antimuon have a mass of 105.66 MeV/$c^2$. (Assuming the particles are slow moving)

   (a) The two photons will each have energies of 105.66MeV.

   (b) Using $E = h\nu = hc/\lambda$

   $\lambda = hc/E = 6.62 \times 10^{-34} \times 3\times10^{8}/(105.66 \times 10^{6} \times 1.6\times10^{-19}) = 4.2 \times 10^{-15}$ m

   (c) Two photons are required to conserve momentum

   (d) They must travel in opposite directions to conserve momentum

   (e) The photons are in the gamma radiation part of the e/m spectrum.

5. (a) n → p + $e^-$ + ______

| | CHARGE | BARYON No. | LEPTON No. |
|---|---|---|---|
| LHS | 0 | 1 | 0 |
| RHS | 0 | 1 | 1 |
| Balance | 0 | 0 | -1 |

An anti-neutrino is required on the RHS to balance

(b) ___ + n → ____ + $e^-$

| | CHARGE | BARYON No. | LEPTON No. |
|---|---|---|---|
| LHS | 0 | 1 | 0 |
| RHS | -1 | 0 | 1 |
| Balance | 1 | -1 | -1 |

electron antineutrino(LHS) and proton (RHS)

(c) $\pi^+$ → $\mu^+$ + ____

| | CHARGE | BARYON No. | LEPTON No. |
|---|---|---|---|

| | | | |
|---|---|---|---|
| LHS | 1 | 0 | 0 |
| RHS | 1 | 0 | 1 |
| Balance | 0 | 0 | -1 |

A muon antineutrino is given off.

(d) p → n + $\nu_e$ + _____

| | CHARGE | BARYON No. | LEPTON No. |
|---|---|---|---|
| LHS | 0 | 1 | 1 |
| RHS | 1 | 1 | 0 |
| Balance | 1 | 0 | -1 |

An antimuon

6. Each $\gamma$–ray must have energy of 511keV (the rest energy of an electron and positron). To conserve momentum two $\gamma$–rays are produced travelling in opposite directions.

7. Positrons will travel anti-clockwise

8. Yes an object can accelerate while keeping the same speed, it they are undergoing circular motion at constant angular velocity.

9. Conservation of momentum is violated – the particles have momentum in the y-direction (toward top of page) which they didn't possess before the collision.

10. (a) Friction is caused by residual electromagnetic interactions between the atoms of the two materials. The force carriers are photons and W and Z bosons.

    (b) Nuclear bonding is caused by residual strong interactions between the various parts of the nucleus. The force carriers are gluons.

    (c) The planets orbits due to gravitons.

11. (a) Weak and Gravity interactions act on neutrinos

    (b) Weak (W+, W-, and Z) interactions have heavy carriers

    (c) All of interactions act on the protons in you

12. Gluons cannot be isolated because they carry colour charge themselves.

13. Gravitons are hypothetical particles to explain the 'force' of gravity. They have not been observed. (Gluons have been observed indirectly.)

## Problem Set 15.2: General revision questions

1. Using $\lambda = \frac{hc}{pc}$

   Where $pc = \sqrt{2.E_K.m_0c^2}$

   Here $E_K = 7.0 \text{ x } 10^{12}$ eV
   $pc = 1.1469\text{x}10^{11}$ eV
   $m_0c^2 = 511 \text{ x } 10^3$ eV
   $hc = 1239.84$ eV.nm (this is a constant)
   $l = 1.08 \text{ x } 10^{-17}$ m

2. Using $\frac{v}{c} \approx 1 - \frac{1}{2}\left(\frac{m_0c^2}{E_{tot}}\right)^2$ for v ≈ c

   Where $E_{tot} \approx E_K = 3.00 \text{ x } 10^9$ eV and $m_0c^2 = 5.11 \text{ x } 10^5$ eV
   $v = 0.999999985493c$

3. Using $m_{Rel} = g.m_0$ where $g = 707.1$ and $m_0 = 1.67 \text{ x } 10^{-27}$ kg
   $m_{Rel} = 1.18 \text{ x } 10^{-24}$ kg.

4. $E = 7.53 \text{ x } 10^{-13}$ J
   $m = E/c^2$
   Mass = $8.38 \text{ x } 10^{-30}$ kg

5. (a). $m_ec^2 = 8.19 \text{ x } 10^{-14}$ J, $5.11 \text{ x } 10^5$ eV
   (b).$gm_ec^2 = 3.12\text{x } 10^{-13}$J, $1.95 \text{ x } 10^6$ eV
   (c). $E_K = (g\text{-}1)\, m_ec^2 = 2.303 \text{ x } 10^{-13}$ J, $1.44 \text{ x } 10^6$ eV

6. Using: $\frac{v}{c} \approx \sqrt{1 - \left(\frac{m_0c^2}{E_{tot}}\right)^2}$

   $E_{tot} = E_k + m_ec^2$
   $E_K = 40{,}000$ eV
   (a). $v_{max} = 0.374$c
   (b). 40,000 eV

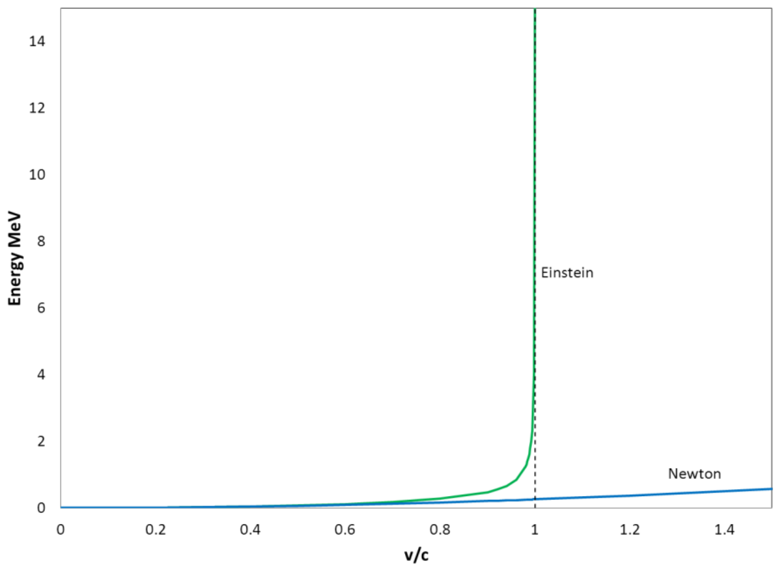
7. No energy is released – 605 MeV is required to make this reaction occur:
   (139.6 + 938.3) - (1189.4 + 493.7) = -605MeV

8. Mass Pa236 = 236.04868 u
   Mass U236 = 236.045568 u
   Mass difference = 0.003112 u
   $Dmc^2 = = 2.9$ MeV
   KE of recoil nucleus = approx. 33eV which is negligible
   E beta = 2.9 MeV
   V beta = 0.989c

9. g = 707.1 $m_{rel} = 1.18 \text{ x}10^{-24}$ kg

10. $2.16 \text{ x } 10^{-23}$ kg 0.00209 km

11. In the Synchrotron electrons are accelerated to velocities approaching the velocity of light. The graphs of both the non-relativistic energy and the relativistic energy are shown



12. (a). 0.511 MeV
    (b).$p_{rel}$ = 2.05 x $10^{-14}$ kg.m/s' $p_{classical}$ = 2.73 x$10^{-22}$ kg.m/s
    (c). 6.15 x$10^{-06}$ J, 3.84 x$10^{13}$ eV

13. See problem 2.

14. It is moving away (red shifted)

    Using: $\frac{v}{c} = \frac{\left(\frac{\lambda_0}{\lambda}\right)^2 - 1}{\left(\frac{\lambda_0}{\lambda}\right)^2 + 1}$

    v = 0.72c (moving apart)

15. Wavelength green light = 540nm (±30nm)
    Wavelength red light = 700nm (±30nm)
    v = 0.25c toward the light

16. Relativistic mass =2.00 x$10^{-30}$ kg
    KE: 9.77 x$10^{-14}$ J, 6.10 x$10^{5}$ eV

17. Gamma x 26 ms = 3.2 x 26 ms = 83 ms

19. See 18 – note here the half-life is stated at 260 ms not 26 ms.
    (a) They will appear to have a half-life of 830 ms.
    (b) distance travelled = 0.95 x c m/s x 830 x $10^{-9}$ s = 236m
    (c). 74m

20. (a). Toward the Earth
    (b). 0.2c
    (c). Apart
    (d) 0.24c