

# **AQA Physics A-level**

## Section 2: Particles and Radiation Notes

## 3.2.1 Particles

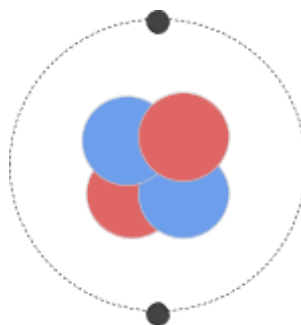
### 3.2.1.1 - Constituents of the atom

An atom is formed of 3 constituents: **protons, neutrons and electrons**. At the centre of an atom is a nucleus formed of protons and neutrons, therefore they are known as nucleons, whereas electrons orbit the nucleus in shells.

These particles have properties which can be described in two ways, in SI units and relative units, as shown below:

Particle	Charge (C)	Relative Charge	Mass (kg)	Relative Mass	Specific Charge (Ckg <sup>-1</sup> )
Proton	$+1.6 \times 10^{-19}$	+1	$1.67 \times 10^{-27}$	1	$9.58 \times 10^7$
Neutron	0	0	$1.67 \times 10^{-27}$	1	0
Electron	$-1.6 \times 10^{-19}$	-1	$9.11 \times 10^{-31}$	0.0005	$1.76 \times 10^{11}$

$$\text{Specific charge} = \frac{\text{Charge}}{\text{Mass}}$$



The **specific charge** of a particle is the charge-mass ratio, and is calculated by dividing a particle's charge by its mass.

For example:

A proton has a charge of  $+1.6 \times 10^{-19} \text{ C}$ , and a mass of  $1.67 \times 10^{-27} \text{ kg}$ .

$$\text{So its specific charge} = \frac{1.6 \times 10^{-19}}{1.67 \times 10^{-27}} = 9.58 \times 10^7 \text{ Ckg}^{-1}$$

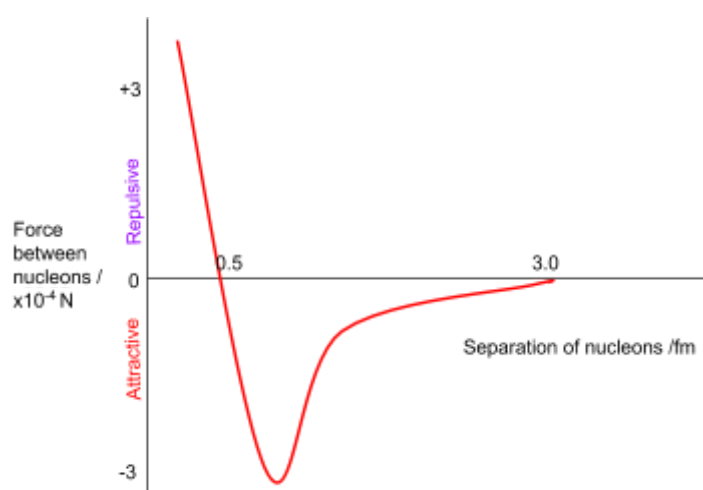
The proton number is the number of protons in an atom and is denoted by  $Z$ , while the nucleon number is the number of protons and neutrons, denoted by  $A$ . These will often be shown in the form: where 'X' is the symbol for the element.



**Isotopes** are atoms with the same number of protons but different numbers of neutrons. For example, carbon-14 is a radioactive isotope of carbon, which can be used to find the approximate age of an object containing organic material. This is done through **carbon dating**, which involves calculating the percentage of carbon-14 remaining in the object, and using the known starting value of carbon-14 (which is the same for all living things) and its half-life to calculate an approximate age.

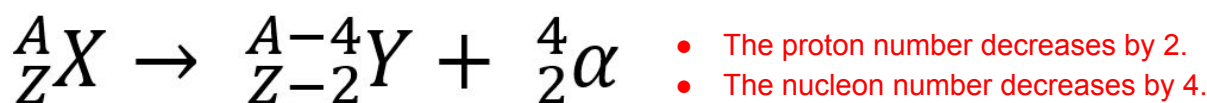
### 3.2.1.2 - Stable and unstable nuclei

The **strong nuclear force (SNF)** keeps nuclei stable by counteracting the electrostatic force of repulsion between protons in the nucleus (as they have the same charge). It only acts on nucleons and has a very short range, where it is attractive up to separations of 3 fm, but repulsive below separations of 0.5 fm, which is demonstrated in the graph below:

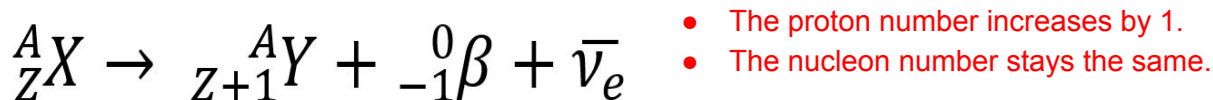


**Unstable nuclei** are those which have **too many of either protons, neutrons or both** causing the SNF to not be enough to keep them stable, therefore these nuclei will decay in order to become stable. The type of decay the nuclei will experience depends on the amount of each nucleon in them.

**Alpha decay** occurs in large nuclei, with too many of both protons and neutrons. A general equation for alpha decay is:



**Beta-minus decay** occurs in nuclei which are neutron-rich (have too many neutrons). A general equation for beta-minus decay is:



At first, scientists believed that only an electron (beta-minus particle) was emitted from the nucleus during beta-minus decay, however observations of the energy levels of the particles before and after the decay showed that energy was not conserved. This does not follow the principle of conservation of energy, and therefore neutrinos were hypothesised to account for this, and later they were observed.

### 3.2.1.3 - Particles, antiparticles and photons

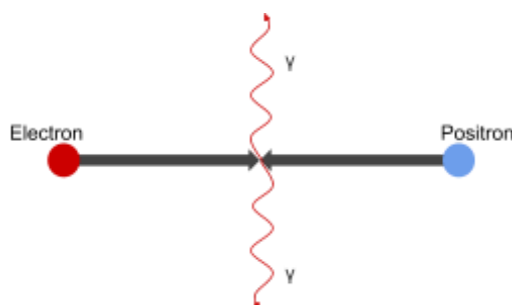
For every type of particle there is an **antiparticle** which has the **same rest energy and mass** but all its other **properties are opposite** the particles. For example, the positron is the antiparticle of the electron, and an electron antineutrino is the antiparticle of a neutrino; this is how their properties compare:

Particle	Mass (kg)	Rest energy (Mev)	Charge (C)
Electron ( $e^-$ )	$9.11 \times 10^{-31}$	0.511	$-1.6 \times 10^{-19}$
Positron ( $e^+$ )	$9.11 \times 10^{-31}$	0.511	$+1.6 \times 10^{-19}$
Electron neutrino ( $\nu_e$ )		0	0
Electron antineutrino ( $\bar{\nu}_e$ )		0	0

Electromagnetic radiation travels in packets called **photons**, which transfer energy and have no mass. The energy of photons is directly proportional to the frequency of electromagnetic radiation, as shown in the equation:

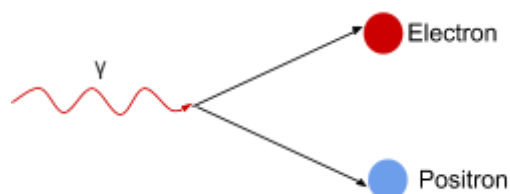
$$E = hf = \frac{hc}{\lambda} \quad \text{where } h \text{ is the planck constant, which is equal to } 6.63 \times 10^{-34} \text{ Js.}$$

**Annihilation** is where a particle and its corresponding antiparticle collide, as a result their masses are converted into energy. This energy, along with the kinetic energy of the two particles is released in the form of 2 photons moving in opposite directions in order to conserve momentum.



An important example of an application of annihilation is in a PET scanner, which allows 3D images of the inside of the body to be taken, therefore making medical diagnoses easier. This is done by introducing a positron-emitting radioisotope into the patient, as positrons are released they annihilate with electrons already in the patients system, emitting gamma photons which can easily be detected.

**Pair production** is where a photon is converted into an equal amount of matter and antimatter. This can only occur when the photon has an energy greater than the total rest energy of both particles, any excess energy is converted into kinetic energy of the particles.



### 3.2.1.4 - Particle interactions

There are four fundamental forces: **gravity, electromagnetic, weak nuclear and strong nuclear.**

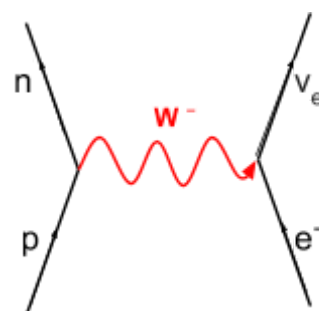
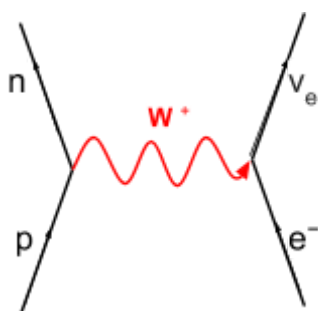
Forces between particles are caused by **exchange particles**. **Exchange particles** carry energy and momentum between the particles experiencing the force and each fundamental force has its own exchange particles. A good example to think about to describe repulsion, is to imagine an exchange as a heavy ball being thrown from one person to another, as the ball is thrown it carries momentum to the second person causing them to move back. This same principle can be applied to describe attraction, but instead of a heavy ball, the exchange particle is a boomerang.

Interaction	Exchange particle	Range (m)	Acts on
Strong	Gluon	$3 \times 10^{-15}$	Hadrons
Weak	W boson ( $W^+$ or $W^-$ )	$10^{-18}$	All particles
Electromagnetic	Virtual photon ( $\gamma$ )	Infinite	Charged particles
Gravity	Graviton (not on specification)	Infinite	Particles with mass

The weak nuclear force is responsible for beta decay, electron capture, and electron-proton collisions, all of which can be represented as the particle interaction diagrams below.

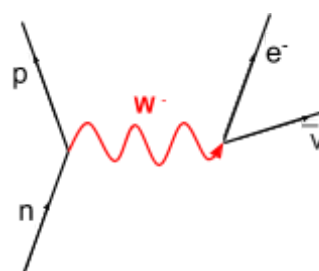
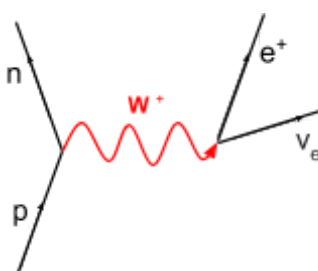
**Electron capture:**  $p + e^- \rightarrow n + \nu_e$     **Electron-proton collision:**

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



As shown above, the equations for electron capture and an electron-proton collision are the same, however a different exchange particle is used.

**Beta-plus decay:**  $p \rightarrow n + e^+ + \nu_e$     **Beta-minus decay:**  $n \rightarrow p + e^- + \bar{\nu}_e$

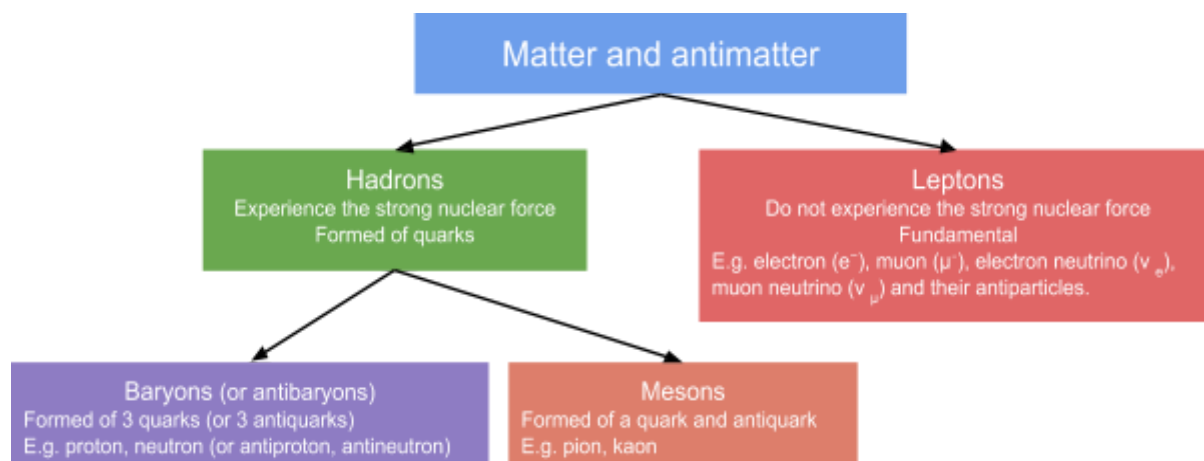


### 3.2.1.5 - Classification of particles

All particles are either **hadrons** or **leptons**. Their differentiating property is that **leptons are fundamental particles**, meaning they cannot be broken down any further, and they **do not** experience the strong nuclear force. On the other hand, hadrons are formed of quarks (quarks are fundamental particles), and hadrons experience the strong nuclear force.

**Hadrons** can be further separated into baryons, antibaryons and mesons. **Baryons** are formed of 3 quarks, **antibaryons** are formed of 3 antiquarks while **mesons** are formed from a quark and antiquark.

The particles you need to know about are summarised in the diagram below:



The **baryon number** of a particle, shows whether it is a baryon (if 1), antibaryon (if -1) or not a baryon (if 0). **Baryon number is always conserved in particle interactions.**

The **proton is the only stable baryon**, therefore all baryons will eventually decay into a proton either directly or indirectly.

The **lepton number** of a particle, shows whether it is a lepton (if 1), antilepton (if -1) or not a lepton (if 0). There are two types of lepton number you need to know, electron lepton number and muon lepton number, which represent the named particle. **Lepton number is always conserved in particle interactions.**

A **muon** is sometimes known as a “heavy electron”, and **muons decay into electrons.**

**Strange particles** are particles which are **produced by the strong nuclear interaction but decay by the weak interaction.** The only strange particles you are expected to know about are kaons, which decay into pions, through the weak interaction.

**Strangeness** is a property of particles, which shows that strange particles must be created in pairs, as strangeness must be conserved in strong interactions. However, in weak interactions strangeness can change by 0, +1 or -1.

In order to investigate particle physics, particle accelerators may be built however as these are very expensive to build and run, and also produce huge amounts of data, **scientific investigations rely on collaboration of scientists internationally.**

### 3.2.1.6 - Quarks and antiquarks

As mentioned above, quarks are fundamental particles which make up hadrons. Each type of quark has different properties, and you need to be aware of 3 types of quark and antiquark.

For the below table, the properties of the respective antiquarks have the opposite sign:

Type of quark	Charge	Baryon number	Strangeness
Up (u)	$+\frac{2}{3}e$	$+\frac{1}{3}$	0
Down (d)	$-\frac{1}{3}e$	$+\frac{1}{3}$	0
Strange (s)	$-\frac{1}{3}e$	$+\frac{1}{3}$	-1

Quarks are combined to form baryons and mesons.

For example, the quark combination **uud**, will form a proton. This is because the overall charge becomes  $+e$ , and the overall baryon number becomes  $+1$ , meaning the resultant is a baryon with a charge of  $+e$ , which is a proton.

The same logic can be applied for the quark combination **udd**, which forms a neutron.

To find the quark combination of an antibaryon, if you know the quark combination of the baryon, is to simply **change the quarks into their respective antiquarks**. This is also true for mesons.

You also need to be aware of the following quark combinations for mesons:

Particle	Quark combination(s)	Charge	Strangeness
$\pi^0$	$u\bar{u}$ or $d\bar{d}$	0	0
$\pi^+$	$u\bar{d}$	+1	0
$\pi^-$	$\bar{u}d$	-1	0
$k^0$	$d\bar{s}$	0	+1
$k^+$	$u\bar{s}$	+1	+1
$k^-$	$\bar{u}s$	-1	-1

As all baryons decay into protons, a neutron will decay into a proton. The equation for this decay is:  $n \rightarrow p + e^- + \bar{\nu}_e$

### 3.2.1.7 - Applications of conservation laws

These properties **must always be conserved** in particle interactions:

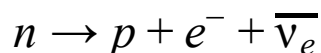
- Energy and momentum
- Charge
- Baryon number
- Electron lepton number
- Muon lepton number

Strangeness must only be conserved during strong interactions.

To show these conservation laws are obeyed in an interaction, you must find the value of each property before and after the interaction and make sure they are equal.

For example, beta-minus decay:

(as this is a weak interaction, strangeness does not need to be conserved)

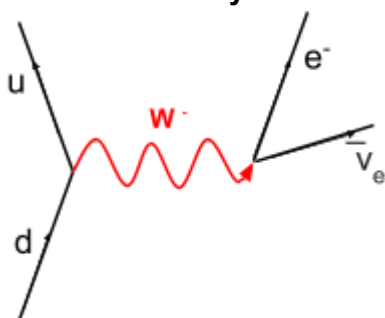


	Charge	Baryon number	Electron lepton number	Muon lepton number	Strangeness
Before interaction	0	1	0	0	0
After interaction	1-1+0=0	1+0+0	0+1-1	0+0+0	0+0+0
Change	0	0	0	0	0

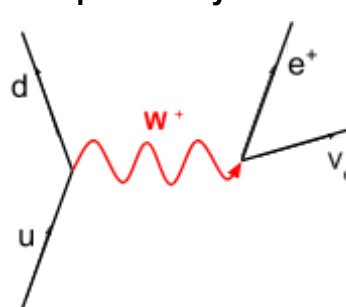
**All the conservation laws are obeyed therefore this interaction is possible.**

Beta-minus and beta-plus decay are both caused by the weak interaction because there is a change of quark type. This can be shown in the below diagrams:

### Beta-minus decay



### Beta-plus decay



In beta-minus decay, for a neutron to change into a proton, a down quark changes into an up quark. And vice versa in beta-plus decay.

## 3.2.2 Electromagnetic radiation and quantum phenomena

### 3.2.2.1 - The photoelectric effect

The **photoelectric effect** is where photoelectrons are emitted from the surface of a metal after light above a certain frequency is shone on it. This certain frequency is different for different types of metals and is called the **threshold frequency**.

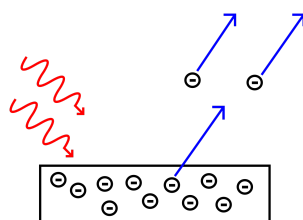


Image source: [Wolfmankurd, CC BY-SA 3.0](https://www.wolframkurd.com/)

The threshold frequency couldn't be explained by the wave theory, as it suggests that any frequency of light should be able to cause photoelectric emission as the energy absorbed by each electron will gradually increase with each incoming wave. However, it could be explained by the photon model of light which suggested that:

- EM waves travel in **discrete packets called photons**, which have an energy which is directly proportional to frequency.
- **Each electron can absorb a single photon**, therefore a photoelectron is only emitted if the frequency is above the threshold frequency.
- If the intensity of the light is increased, if the frequency is above the threshold, more photoelectrons are emitted per second.

The **work function** of a metal is the minimum energy required for electrons to be emitted from the surface of a metal, and it is denoted by  $\phi$ .

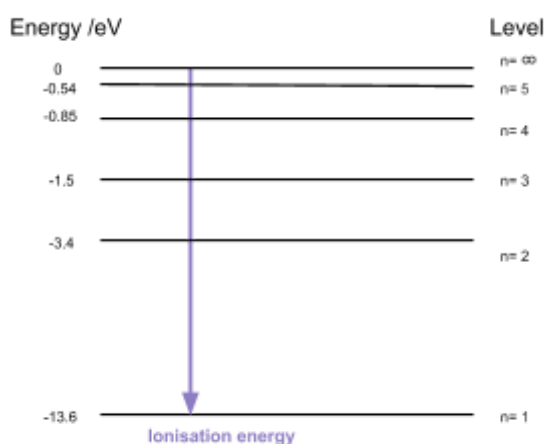
The **stopping potential** is the potential difference you would need to apply across the metal to stop the photoelectrons with the maximum kinetic energy. Measuring stopping potential allows you to find the maximum kinetic energy of the released photoelectrons, as

$E_{k(max)} = eV_s$ . Where  $V_s$  is the stopping potential and  $e$  is the charge of an electron. This is derived using the fact that  $energy = charge \times voltage$ .

The photoelectric equation is  $E = hf = \Phi + E_{k(max)}$ , and it shows the relationship between the work function, maximum kinetic energy and the frequency of light.

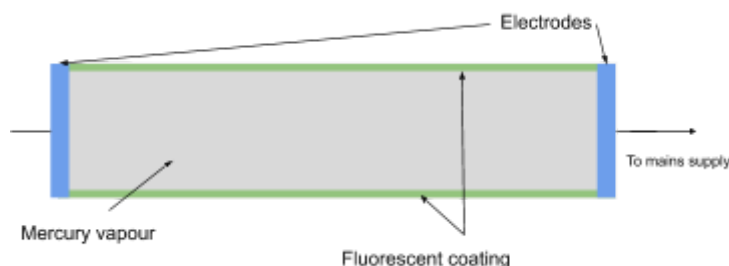
### 3.2.2.2 - Collisions of electrons with atoms

Electrons in atoms can only exist in **discrete energy levels**. These electrons can gain energy from collisions with free electrons, which can cause them to move up in energy level, this is known as **excitation**, or they can gain enough energy to be removed from the atom entirely, this is called **ionisation**. Ionisation occurs if the energy of the free electron is greater than the **ionisation energy**.



If an electron becomes excited, it will quickly return to its original energy level (the ground state), and therefore release the energy it gained in the form of a photon.

An example of a practical use of excitation is in a fluorescent tube in order to produce light. Fluorescent tubes are filled with mercury vapour, across which a high voltage is applied, as shown in the below diagram:



This voltage accelerates free electrons through the tube, which collide with the mercury atoms causing them to become ionised, releasing more free electrons. The free electrons collide with the mercury atoms, causing them to become excited. When they de-excite they release photons, most of which are in the UV range. The (phosphorous) **fluorescent coating** on the inside of the tube, absorbs these UV photons and therefore electrons in the atoms of the coating become excited and de-excite releasing photons of visible light.

When describing the energy difference between energy levels, the values of energy are very small, therefore the unit, electron volts (eV) is used instead of joules (J). An **electron volt** is defined as the **energy gained by one electron when passing through a potential difference of 1 volt**.

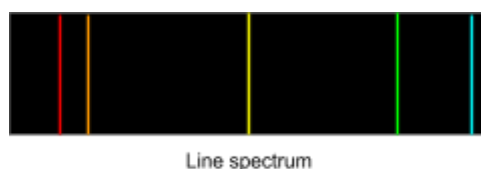
We know that  $energy = charge \times voltage$ , therefore  $1 eV = e \times 1 = 1.6 \times 10^{-19}$ .

And so to convert from eV to joules, multiply your value by  $1.6 \times 10^{-19}$ .

To convert from joules to eV, divide your value by  $1.6 \times 10^{-19}$ .

### 3.2.2.3 - Energy levels and photon emission

By passing the light from a fluorescent tube through a diffraction grating or prism, you get a **line spectrum**. Each line in the spectrum will represent a different wavelength of light emitted by the tube. As this spectrum is not continuous but rather contains only **discrete values of wavelength**, the only photon energies emitted will correspond to these wavelengths, therefore this is evidence to show that electrons in atoms can only transition between discrete energy levels.



Line spectrum

You can also do this by passing white light through a cooled gas however you would get a **line absorption spectrum**, which looks like a continuous spectrum of all possible wavelengths of light, with black lines at certain wavelengths. These lines represent the possible differences in energy levels as the atoms in the gas can only absorb photons of an energy equal to the exact difference between two energy levels.

The difference between two energy levels is equal to a specific photon energy emitted by a fluorescent tube, or absorbed in a line absorption spectrum. Therefore:  $\Delta E = E_1 - E_2$ , where  $E_1$  and  $E_2$ , represent energy levels:

$$\text{As } E = hf, hf = E_1 - E_2$$

### 3.2.2.4 - Wave-particle duality

Light can be shown as having **both** wave and particle properties. Examples of light acting as a wave are **diffraction and interference**, while an example of light acting as a particle is the **photoelectric effect**.

Electrons can also be shown as having **both** wave and particle properties, as the wave nature of electrons can be observed through **electron diffraction**, as only waves can experience diffraction.



The electron diffraction interference pattern forms concentric rings

De Broglie hypothesised that if light was shown to have particle properties, then particles should also have wave-like properties, and he wrote an equation relating the wavelength ( $\lambda$ ) of an object to its momentum ( $mv$ ):

$$\lambda = \frac{h}{mv} \quad \text{where } h \text{ is the planck constant.}$$

Using the above equation you can see how the amount of diffraction changes as a particle's momentum changes. When the momentum is increased, the wavelength will decrease, and therefore the amount of diffraction decreases, so the concentric rings of the interference pattern become closer. Whereas, when momentum is decreased, the wavelength increases, the amount of diffraction increases so the rings move further apart.

Scientists did not always agree that matter had this wave-particle duality, however as time went on and experimental evidence for this phenomena was gathered (notably electron diffraction and the photoelectric effect), it was eventually accepted. **Knowledge and understanding of any scientific concept changes over time in accordance to the experimental evidence gathered** by the scientific community. However, these pieces of experimental

evidence must first be published to allow them to be **peer-reviewed by the community to become validated**, and eventually accepted.