Higher Physics

Unit 2  Particles and Waves
Section 4  Wave Particle Duality
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Note Making

Make a dictionary with the meanings of any new words.

History – The nature of light

1. Write a short note on the history of light. Include the relevant discoveries. No more than half a page.

Wave particle duality

1. What are the main differences between the classical ‘clockwork’ model and the new quantum mechanics model?

The photoelectric effect

1. What is meant by the photoelectric effect and state the conditions needed to obtain the emission of electrons.
2. State the meaning of threshold frequency and describe an experiment to measure it. Include the graphs on page 8.

Photons

1. Define the terms quanta and photons and copy the worked example on page 10.

Threshold frequency and work function

1. Explain the relationship between the threshold frequency and work function. Copy down the worked example.
Section 4  Wave Particle Duality

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Section 4  Wave Particle Duality

History – The nature of light

Exactly what is light? This question has troubled scientists since the time of the ancient Greeks, when Aristotle and Democritus started to publicly theorise. In ancient India, the Hindu schools of Samkhya and Vaisheshika were similarly divided between the two main theories: light is a wave or light is a stream of particles. Aristotle considered that light was a disturbance in the element, air, i.e. a wave. Democritus, who originally proposed the concept of atoms, not surprisingly thought that light is made up of ‘corpuscles’ or tiny particles of some form. At various points in history one view has held sway over the other as new experimental evidence came to light. For many of the properties of light it doesn’t actually matter which view we take. Both theories can describe light as rays which travel in straight lines. Euclid was the first to develop a detailed theory of reflection using such rays. Nobody was able to develop theories of light much further as more intricate experimentation was not possible.

At the beginning of the 11th century the Arabic scientist Alhazen developed a full theory of optics (reflection, refraction and diffraction) based on a particle perspective. However, once again there was no significant progress for many centuries until Newton and his contemporaries locked horns in the 17th century. Newton considered that the particle nature of light was evident since only particles could travel in such perfectly straight lines. Refraction was more difficult to explain but he postulated that there would be a lateral acceleration on the particles as they changed medium. René Déscartes, Robert Hooke and Augustin-Jean Fresnel, however, favored a wave explanation and showed that refraction can be easily explained if waves change speed on entering a different medium. Their theories held sway for the coming centuries.

The 19th century seemed to finally sound the death knell of the particle theory. Firstly, Thomas Young performed his double-slit
experiment showing that light could interfere, an effect that is impossible to explain using particles. (You will learn more about this important experiment later in the unit.) Christiaan Huygens developed Fresnel’s wave theories to give a full explanation of this experiment from a wave perspective. Later, James Clark Maxwell developed his theories of electromagnetic waves as a special interlocked pattern of oscillating electric and magnetic fields. Furthermore, the speed of these waves was shown to be exactly the same as the speed of light, which was being measured with increasing accuracy by Armand Fizeua, Léon Foucault and Albert Michelson. Electricity and magnetism were in fact two different aspects of the same phenomenon and would become one field of study, electromagnetism. These electromagnetic waves were taken to be the final word in the description of light.

However, within 20 years Heinrich Hertz had observed that electromagnetic radiation could knock electrons off the surface of a metal plate in what came to be known as the photoelectric effect. This in itself didn’t pose any problems to the wave theory of light, but after the turn of the century more detailed study of this effect by Philipp Lenard showed that the speed of the ejected electrons did not depend on the intensity of the light but its frequency. This could not be explained using Maxwell’s laws and a wave view of light.

At the same time Max Planck was studying a seemingly separate problem called black body radiation. This is the radiation emitted by any hot object and cannot be fully explained using Maxwell’s equations. Instead it requires the introduction of quantisation, i.e. the idea that electromagnetic energy comes in tiny packets called quanta or now more commonly photons. The energy of these photons is directly proportional to their frequency and the constant of proportion is now known as the Planck constant. The size of these packets is far too small for us to easily observe in everyday life.

In 1905 Albert Einstein applied Planck’s theories to the photoelectric effect and explained why the speed of the electrons depended on the frequency of the light by considering the light as being made up of particles or photons. Interestingly, it was this, rather than his now more famous theories of relativity, for which he was awarded his first Nobel prize. However, that was 16 years later and at first his theories were not widely accepted. It wasn’t until 1915 that experimental evidence from Robert Millikan and further theories from Arthur
Compton and Peter Debye gave weight to Einstein’s explanation of the photoelectric effect. The term ‘photon’ would not become widely used until a further decade later.

**Wave–particle duality**

We have seen evidence, therefore, of the particle nature of light. However, there is also evidence of the wave-like nature of light. How are we to marry these seemingly contradictory viewpoints? Modern physics now takes the view that light can act both like a wave and like a particle without contradiction. It depends on how we test it. If we look for evidence that it is a wave, we can find it. But also, if we look for evidence that it is a particle we can find that too. The universe seems to be made up of things that are both particle-like and wave-like. This is known as wave–particle duality.

It should come as no surprise, therefore, to find that objects that have traditionally been thought of as particles, e.g. electrons, can also behave like waves. Their wavelength is so small that it is not observed in everyday life, but if we can create gaps that are small enough, we can observe diffraction of electrons and other particles. Louis DeBroglie initially developed these theories in the early 20th century. Building on the work of Einstein and Planck, he was able to explain many of the mysteries of the structure of the atom, such as line spectra, which you will study later in this unit.

This was also the birth of quantum mechanics, heralding a massive change in how we perceive the universe. Gone was the clockwork model where, in theory, every electron, proton, atom etc. could be tracked through time as long as we had a powerful enough computer. If we measured where everything was at a certain time and what speed it was going at we could work out where it would be any time later. The modern view of the subatomic scale uses probabilities to describe both the position and speed of particles, and nothing can be known with absolute certainty. (You may wish to research some of the work carried out by Heisenberg in this field.) The subatomic world is a fuzzy one where little is definite.
Photoelectric emission

Sometimes when electromagnetic radiation strikes a surface, electrons are emitted. This can be used to detect radiation and is the basis of devices such as light meters and photomultipliers. Much more importantly, however, is its place in the development of our understanding of the nature of light (and electromagnetic radiation in general).

The photoelectric effect

It is found that a negatively charged clean zinc plate loses its charge if it is illuminated with ultraviolet (UV) light. The charge is measured by the zinc plate being attached to a coulometer.

The effect does not occur with a positively charged coulometer illuminated with UV light, nor does it happen with a negatively charged coulometer illuminated by light in the visible region.

This is an example of the photoelectric effect.
A further observation is that UV radiation with a high irradiance causes the negatively charged coulometer to discharge more quickly.

From these results it seems that UV radiation causes electrons to be ejected (photoemission) from the zinc (since the coulometer loses negative charge) – the more intense the UV radiation the more electrons are ejected.

We can see that electrons are emitted if the following conditions are met:

- the radiation must have a high enough frequency (or short enough wavelength)
- the surface must be suitable – the energy in UV radiation will not eject electrons from iron, copper, lead etc., but will from sodium and potassium, although these are a bit tricky to use!

In general, the photoelectric effect is the removal of electrons from a metal surface by electromagnetic radiation.
Threshold frequency

A further curious feature of photoemission is the fact that even very low irradiance UV will cause some photoemission from zinc, but very high irradiance visible light will not. The requirement for photoemission therefore depends not on the irradiance of the radiation, but on the frequency.

The following apparatus can be used to study photoemission in more detail. Rather than letting the ejected electrons escape, they are attracted to a positive plate, forming part of a circuit.

The UV radiation passes through the quartz window (a glass window would absorb the radiation) and strikes the photocathode, which is made from zinc. This causes photoelectrons to be emitted. The d.c. supply creates an electric field between the cathode and anode, which in turn causes the electrons to move across the ‘gap’ to the anode, producing a current, which is registered by a milliammeter. This is called a photoelectric current.
The minimum frequency that will produce photoemission from a particular surface is called the **threshold frequency** \( (f_0) \). Beyond this, an increase in frequency will cause an increase in the speed of the electrons being emitted. This in turn leads to an increase in current. This is a square-root relationship since \( v \propto \sqrt{E_v} \).

It is found that the photoelectric current (i.e. the stream of electrons) is directly proportional to the irradiance of the radiation:

The photoelectric current is a reflection of the number of electrons emitted from the surface, so the greater the irradiance of the radiation the greater the number of electrons emitted.
**Photons**

The existence of the photoelectric effect, which was discovered by Lenard in 1899, caused a problem with the wave theory of light. To eject an electron from a metal requires a precise amount of energy. A weak UV source has sufficient energy to do this for a clean zinc surface, but no matter how high the intensity of the white light is, no electrons are ejected. This is true even though, over a period of time, the ‘total’ energy of the white light is greater than that of the UV.

In 1904 Einstein applied an earlier idea of Planck to the phenomenon and proposed that light was not a continuous wave, but existed as a stream of ‘packets’ or ‘quanta’. These quanta are called photons and are particles of light (and other electromagnetic radiation), although unlike other particles they have no mass.

Each photon still has a frequency and wavelength associated with it and the energy contained in each photon is given by:

\[ E = hf \]

where \( h \) is the Planck constant, \( h = 6.63 \times 10^{-34} \) Js

*Note:* You do not need to know the value of this constant, it will be provided for you on the data sheet.
Worked example

1. What is the photon energy for red light? \( (f = 4.2 \times 10^{14} \text{ Hz}) \)

\[
E = hf \\
E = 6.63 \times 10^{-34} \times 4.2 \times 10^{14} \\
E = 2.78 \times 10^{-19} \text{ J}
\]

*Note:* Photons from the visible part of the electromagnetic spectrum will have energy of the order \( 10^{-19} \text{ J} \).

You may remember that photons are also the exchange particles for the electromagnetic force. The electromagnetic force from the light source has affected the electrons from the metal plate through the mediation of the photon.

Threshold frequency and work function

As stated earlier, it is found that for a particular metal there is a minimum frequency of radiation required in order to eject an electron from it. Photons at or above this threshold frequency will eject electrons; those with less than this frequency will not. Clearly therefore there is a **threshold energy**, i.e. the energy that photons must have if they are to eject electrons.

This threshold energy is called the **work function** for the surface:

work function = \( hf_0 \)

An electron released by a photon having this level of energy will have absorbed sufficient energy to escape but will have no energy ‘left over’, i.e. it will have zero kinetic energy.
If the energy of the incident photon is greater than the work function, the ‘extra’ energy will appear as kinetic energy of the electron, so:

\[ E_k = hf - hf_0 \]

total energy of photon

energy required to remove electron

Note: The energy transferred to the electrons depends only on the frequency of the photons.

Higher irradiance radiation does not increase the velocity of the electrons; it produces more electrons of the same velocity.

**Worked example**

The work function of a cesium metal surface is $2.16 \times 10^{-19}$ J.

(a) Calculate the minimum frequency of radiation that will emit photoelectrons from this metal.

(b) If light of wavelength 589 nm is incident on the surface, calculate the maximum kinetic energy gained by each photoelectron.

(c) Hence calculate the maximum velocity with which photoelectrons will be emitted from the surface.

($h = 6.63 \times 10^{-34}$ Js; mass of an electron = $9.11 \times 10^{-31}$ kg)
Solution

(a) work function \( hf_0 = 2.16 \times 10^{-19} \)

\[
f_0 = \frac{2.16 \times 10^{-19}}{6.63 \times 10^{-34}} = 3.26 \times 10^{14} \text{ Hz}
\]

(b)

\[
f = \frac{v}{\lambda} = \frac{3 \times 10^8}{589 \times 10^{-9}} = 5.09 \times 10^{14} \text{ Hz}
\]

\[
E_k = hf - hf_0
= 6.63 \times 10^{-34} \times 5.09 \times 10^{14} - 2.16 \times 10^{-19}
= 3.37 \times 10^{-19} - 2.16 \times 10^{-19}
= 1.21 \times 10^{-19} \text{ J}
\]

(c)

\[
\frac{mv^2}{2} = 1.21 \times 10^{-19}
\]

\[
v^2 = 2 \times 1.21 \times 10^{-19} \times 9.11 \times 10^{-31} = 2.66 \times 10^{11}
\]

\[
v = 5.15 \times 10^5 \text{ ms}^{-1}
\]

Note: Remember, electron velocities should not exceed the speed of light!
Wave Particle Duality Problems

Photoelectric effect

1. A ‘long wave’ radio station broadcasts on a frequency of 252 kHz.
   Calculate the period of these waves.
   What is the wavelength of these waves?

2. Green light has wavelength 546 nm.
   Express this wavelength in metres (using scientific notation).
   Calculate:
   the frequency of these light waves
   the period of these light waves.

3. Ultraviolet radiation has a frequency $2.0 \times 10^{15}$ Hz.
   (a) Calculate the wavelength of this radiation.
   (b) Calculate the period of this radiation.

4. Blue light has a frequency of $6.50 \times 10^{14}$ Hz.
   Calculate the energy of one photon of this radiation.

5. Red light has a wavelength of $6.44 \times 10^{-7}$ m.
   Calculate the energy of one photon of this light.

6. A photon of radiation has an energy of $3.90 \times 10^{-19}$ J.
   Calculate the wavelength of this radiation in nm.
7. In an investigation into the photoelectric effect a clean zinc plate is attached to a coulombmeter, as shown.

The threshold frequency of radiation for zinc is $6.50 \times 10^{14}$ Hz.

(a) The zinc plate is initially negatively charged. A lamp is used to shine ultraviolet radiation of frequency $6.7 \times 10^{14}$ Hz onto the zinc plate.

Describe and explain what happens to the reading on the coulombmeter.

(b) The zinc plate is again negatively charged.

Describe and explain the effect each of the following changes has on the reading on the coulombmeter:

(i) moving the ultraviolet lamp further away from the zinc plate
(ii) using a source of red light instead of the uv lamp.

(c) The zinc plate is now positively charged. The uv lamp is again used to irradiate the zinc plate. Describe and explain the effect this has on the positive reading on the coulombmeter.
8. In a study of photoelectric currents, the graph shown was obtained.

What name is given to the frequency $f_o$?

Explain why no current is detected when the frequency of the incident radiation is less than $f_o$.

9. For a certain metal, the energy required to eject an electron from the atom is $3.30 \times 10^{-19}$ J.

Calculate the minimum frequency of radiation required to emit a photoelectron from the metal.

Explain whether or not photoemission would take place using radiation of:

- frequency $4 \times 10^{14}$ Hz
- wavelength $5 \times 10^{-7}$ m.

10. The minimum energy required to remove an electron from zinc is $6.10 \times 10^{-19}$ J.

What is the name is given to this minimum energy?

Calculate the value of $f_o$ for zinc.

Photons with a frequency of $1.2 \times 10^{15}$ Hz strike a zinc plate, causing an electron to be ejected from the surface of the zinc.

Calculate the amount of energy the electron has after it is released from the zinc.

What kind of energy does the electron have after it is released?
11. Radiation of frequency $5.0 \times 10^{14}$ Hz can eject electrons from a metal surface.

Calculate the energy of each photon of this radiation.

Photoelectrons are ejected from the metal surface with a kinetic energy of $7.0 \times 10^{-20}$ J.
Calculate the work function of this metal.

12. An argon laser is used in medicine to remove fatty deposits in arteries by passing the laser light along a length of optical fibre. The energy of this light is used to heat up a tiny metal probe to a sufficiently high temperature to vaporise the fatty deposit.

The laser has a power of $8.0$ W. It emits radiation with a wavelength of $490$ nm.

How much energy is delivered from the laser in 5 seconds?

Calculate the number of photons of this radiation required to provide the 5 s pulse of energy from the 8·0 W laser.
The apparatus shown is used to investigate photoelectric emission from a metal plate when electromagnetic radiation is shone on the plate. The irradiance and frequency of the incident radiation can be varied as required.

![Diagram of apparatus](image)

Explain what is meant by ‘photoelectric emission’ from a metal.

What is the name given to the minimum frequency of the radiation that produces a current in the circuit?

(c) A particular source of radiation produces a current in the circuit. Explain why the current in the circuit increases as the irradiance of the incident radiation increases.

14. State whether each of the following statements is true or false.

(a) Photoelectric emission from a metal occurs only when the frequency of the incident radiation is greater than the threshold frequency for the metal.

(b) The threshold frequency depends on the metal from which photoemission takes place.

(c) When the frequency of the incident radiation is greater than the threshold frequency for a metal, increasing the irradiance of the radiation will cause photoemission from the metal to increase.

(d) When the frequency of the incident radiation is greater than the threshold frequency for a metal, increasing the
irradiance of the radiation will increase the maximum energy of the electrons emitted from the metal.

(e) When the frequency of the incident radiation is greater than the threshold frequency for a metal, increasing the irradiance of the incident radiation will increase the photoelectric current from the metal.
Solutions

Photoelectric effect

1.  
   (a) $3.97 \times 10^{-6}$ s  
   (b) $1.19 \times 10^3$ m

2.  
   (a) $5.46 \times 10^{-7}$ m  
   (b) (i) $5.49 \times 10^{14}$ Hz  
       (ii) $1.82 \times 10^{-15}$ s

3.  
   (a) $1.5 \times 10^{-7}$ m  
   (b) $5.0 \times 10^{-16}$ s

4.  $4.31 \times 10^{-19}$ J

5.  $3.09 \times 10^{-19}$ J

6.  $510$ nm

9.  
   (a) $4.98 \times 10^{14}$ Hz

10.  
    (b) $9.20 \times 10^{14}$ Hz  
     (c) (i) $1.86 \times 10^{-19}$ J

11.  
    (a) $3.3 \times 10^{-19}$ J  
    (b) $2.6 \times 10^{-19}$ J

12.  
    (a) $40$ J  
    (b) $9.9 \times 10^9$