RADIATION AND MATTER

The knowledge and understanding for this unit is given below.

Waves

1. State that the frequency of a wave is the same as the frequency of the source producing it.
2. State that period equals 1/frequency.
3. State that the energy of a wave depends on its amplitude.
4. Use correctly in context the terms: 'in phase', 'out of phase' and 'coherent', when applied to waves.
5. Explain the meaning of: 'constructive interference' and 'destructive interference' in terms of superposition of waves.
6. State that interference is the test for a wave.
7. State that reflection, refraction, diffraction and interference are characteristic behaviours of all types of waves.
8. State the conditions for maxima and minima in an interference pattern formed by two coherent sources in the form:

   Path difference = $n\lambda$ for maxima and

   Path difference = $(n + \frac{1}{2})\lambda$ for minima, where n is an integer.
9. Carry out calculations using the above relationships.
10. Describe the effect of a grating on a monochromatic light beam.
11. Carry out calculations using the grating equation $d\sin\theta = n\lambda$.
12. Describe the principles of a method for measuring the wavelength of a monochromatic light source, using a grating.
13. State approximate values for the wavelengths of red, green and blue light.
14. Describe and compare the white light spectra produced by a grating and a prism.

Refraction of light

1. State that the ratio $\sin\theta_1/\sin\theta_2$ is a constant when light passes obliquely from medium 1 to medium 2.
2. State the absolute refractive index, n, of a medium is the ratio $\sin\theta_1/\sin\theta_2$, where θ_1 is in a vacuum (or air as an approximation) and θ_2 is in the medium.
3. Describe the principles of a method for measuring the absolute refractive index of glass for monochromatic light.
4. Carry out calculations using the relationship for refractive index.
5. State that the refractive index depends on the frequency of the incident light.
6. State that the frequency of a wave is unaltered by a change in medium.
7. State the relationships $\dfrac{\sin\theta_1}{\sin\theta_2} = \dfrac{\lambda_1}{\lambda_2} = \dfrac{\mathrm{v}_1}{\mathrm{v}_2}$

   for refraction of a wave from medium 1 to medium 2.
8. Carry out calculations using the above relationships.
9. Explain what is meant by total internal reflection.
10. Explain what is meant by critical angle θ_c.
11. Describe the principles of a method for measuring a critical angle.
12. Derive the relationship $\sin\theta_c = 1/n$, where θ_c is the critical angle for a medium of absolute refractive index n.
13. Carry out calculations using the above relationship.

Optoelectronics and semiconductors

1. State that the intensity I at a surface on which radiation is incident is the power per unit area.
2. Describe the principles of a method for showing that the intensity is inversely proportional to the square of the distance from a point source.
3. Carry out calculations involving the relationship $I = k/d^2$.
4. State that photoelectric emission from a surface occurs only if the frequency of the incident radiation is greater than some threshold frequency f_o which depends on the nature of the surface.
5. State that for frequencies smaller than the threshold value, an increase in the intensity of the radiation at the surface will not cause photoelectric emission.
6. State that for frequencies greater than the threshold value, the photoelectric current produced by monochromatic radiation is directly proportional to the intensity of the radiation at the surface.
7. State that a beam of radiation can be regarded as a stream of individual energy bundles called photons, each having an energy $E = hf$, where h is Planck's constant and f is the frequency of the radiation.
8. Carry out calculations involving the relationship $E = hf$.
9. Explain that if N photons per second are incident per unit area on a surface, the intensity at the surface $I = Nhf$.
10. State that photoelectrons are ejected with a maximum kinetic energy E_k, which is given by the difference between the energy of the incident photon hf and the work function hf_o of the surface: $E_k = hf - hf_o$.
11. State that electrons in a free atom occupy discrete energy levels.
12. Draw a diagram which represents qualitatively the energy levels of a hydrogen atom.
13. Use the following terms correctly in context: ground state, excited state, ionisation level.
14. State that an emission line in a spectrum occurs when an electron makes a transition between an excited energy level W_2 and a lower level W_1, where
    $W_2 - W_1 = hf$.
15. State that an absorption line in a spectrum occurs when an electron in energy level W_1 absorbs radiation of energy hf and is excited to energy level W_2, where
    $W_2 = W_1 + hf$.
16. Explain the occurrence of absorption lines in the spectrum of sunlight.
17. State that spontaneous emission of radiation is a random process analogous to the radioactive decay of a nucleus.
18. State that when radiation of energy hf is incident on an excited atom, the atom may be stimulated to emit its excess energy hf.
19. State that in stimulated emission the incident radiation and the emitted radiation are in phase and travel in the same direction.
20. State that the conditions in a laser are such that a light beam gains more energy by stimulated emission than it loses by absorption – hence Light Amplification by the Stimulated Emission of Radiation.
21. Explain the function of the mirrors in a laser.
22. Explain why a beam of laser light having a power even as low as 0.1 mW may cause eye damage.

23. State that materials can be divided into three broad categories according to their electrical properties: conductors, insulators and semiconductors.
24. Give examples of conductors, insulators and semiconductors.
25. State that the addition of impurity atoms to a pure semiconductor (a process called doping) decreases its resistance.
26. Explain how doping can form an n-type semiconductor in which the majority of the charge carriers are negative, or a p-type semiconductor in which the majority of the charge carriers are positive.
27. Describe the movement of the charge carriers in a forward/reverse-biased p-n junction diode.
28. State that in the junction region of a forward-based p-n junction diode, positive and negative charge carriers may recombine to give quanta of radiation.
29. State that a photodiode is a solid-state device in which positive and negative charges are produced by the action of light on a p-n junction.
30. State that in the photovoltaic mode, a photodiode may be used to supply power to a load.
31. State that in the photoconductive mode, a photodiode may be used as a light sensor.
32. State that leakage current of a reverse-biased photodiode is directly proportional to the light intensity and fairly independent of the reverse-biasing voltage, below the breakdown voltage.
33. State that the switching action of a reverse-biased photodiode is extremely fast.
34. Describe the structure of an n-channel enhancement MOSFET using the terms: gate, source, drain, substrate, channel, implant and oxide layer.
35. Explain the electrical ON and OFF states of an n-channel enhancement MOSFET.
36. State that an n-channel enhancement MOSFET can be used as an amplifier.

Nuclear reactions

1. Describe how Rutherford showed that:
    a) the nucleus has a relatively small diameter compared with that of the atom
    b) most of the mass of the atom is concentrated in the nucleus.
2. Explain what is meant by alpha, beta and gamma decay of radionuclides.
3. Identify the processes occurring in nuclear reactions written in symbolic form.
4. State that in fission a nucleus of large mass number splits into two nuclei of smaller mass numbers, usually along with several neutrons.
5. State that fission may be spontaneous or induced by neutron bombardment.
6. State that in fusion two nuclei combine to form a nucleus of larger mass number.
7. Explain, using $E = mc^2$, how the products of fission and fusion acquire large amounts of kinetic energy.
8. Carry out calculations using $E = mc^2$ for fission and fusion reactions.

Dosimetry and safety

1. State that the average activity *A* of a quantity of radioactive substance is *N/t*, where *N* is the number of nuclei decaying at the time *t*.
2. State that one becquerel is one decay per second.
3. Carry out calculations involving the relationship $A = N/t$.
4. State that the absorbed dose *D* is the energy absorbed per unit mass of the absorbing material.
5. State that the gray Gy is the unit of absorbed dose and that one gray is one joule per kilogram.
6. State that the risk of biological harm from an exposure to radiation depends on:
   a) the absorbed does
   b) the kind of radiation, e.g. α, β, γ , slow neutron
   c) the body organs or tissues exposed.
7. State that a quality factor *Q* is given to each kind of radiation as a measure of its biological effect.
8. State that the dose equivalent *H* is the product of *D* and *Q* and is measured in sieverts Sv.
9. Carry out calculations involving the relationship $H = DQ$.
10. State that dose equivalent rate = *H/t*.
11. State that the effective dose equivalent takes account of the different susceptibilities to harm of the tissues being irradiated and is used to indicate the risk to health from exposure to ionising radiation.
12. Describe the factors affecting the background radiation level.
13. State that the average annual effective dose equivalent which a person in the UK receives due to natural sources (cosmic, terrestrial and internal radiation) is approximately 2 mSv.
14. State that annual effective dose equivalent limits have been set for exposure to radiation for the general public, and higher limits for workers in certain occupations.
15. Sketch a graph to show how the intensity of a beam of gamma radiation varies with the thickness of an absorber.
16. Describe the principles of a method for measuring the half-value thickness of an absorber.
17. Carry out calculations involving half-value thickness.
18. State that the dose equivalent rate is reduced by shielding or by increasing the distance from a source.

Units, prefixes and scientific notation

1. Use SI units of all physical quantities appearing in the ‘Content Statements’.
2. Give answers to calculations to an appropriate number of significant figures.
3. Check answers to calculations.
4. Use prefixes (p, n, µ, m, k, M, G).
5. Use scientific notation.

Uncertainties

1. State that measurement of any physical quantity if liable to uncertainty.
2. Distinguish between random uncertainties and recognised systematic effects.
3. State that the scale-reading uncertainty is a measure of how well an instrument scale can be read.
4. Explain why repeated measurements of a physical quantity are desirable.
5. Calculate the mean value of a number of measurements of the same physical quantity.
6. State that this mean is the best estimate of a 'true' value of the quantity being measured.
7. State that where a systematic effect is present, the mean value of the measurements will be offset from a 'true' value of the physical quantity being measured.
8. Calculate the approximate random uncertainty in the mean value of a set of measurements using the relationship:

$$\text{approximate random uncertainty in the mean} = \frac{\text{maximum value} - \text{minimum value}}{\text{number of measurements taken}}$$

9. Estimate the scale-reading uncertainty incurred when using an analogue display and a digital display.
10. Express uncertainties in absolute or percentage form.
11. Identify, in an experiment where more than one physical quantity has been measured, the quantity with the largest percentage uncertainty.
12. State that this percentage uncertainty is often a good estimate of the percentage uncertainty in the final numerical result of an experiment.
13. Express the numerical result of an experiment in the form: final value ± uncertainty.

WAVES

Frequency of a wave

The frequency of a wave (f) is the number of complete waves (N) which pass a point in one second. Frequency is measured in hertz (Hz). The frequency of a wave is the same as the frequency of the source producing it.

$$\boxed{f = \frac{N}{t}}$$

Period of a wave

The period of a wave (T) is the time taken for one complete wave to pass a point, or the time taken to produce one complete wave. Period is measured in seconds (s). It is the inverse of the frequency.

$$\boxed{T = \frac{1}{f}}$$

Example

Find the period of a wave with a frequency of 40 Hz.

Period T $= \frac{1}{f} = \frac{1}{40}$ *= 0.025 s.*

Energy of a wave

The energy of a wave depends on its amplitude; the larger the amplitude, the more energy it has. The amplitude of curved water waves decreases as they spread out, since the total energy of the wave is spread out over a larger wavefront.

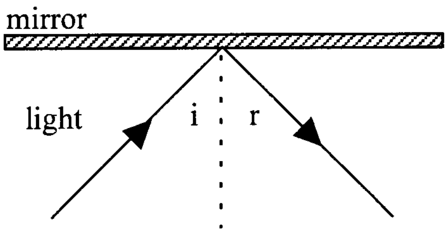
Wave characteristics

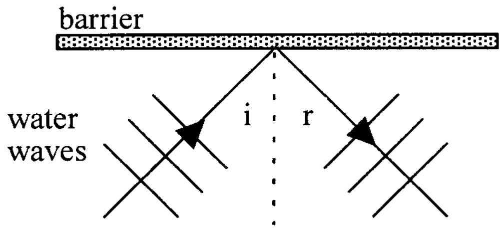
All waves exhibit reflection, refraction, diffraction and interference.

Reflection

Angle of incidence = angle of reflection

i = r





Speed, frequency and wavelength all stay the same.

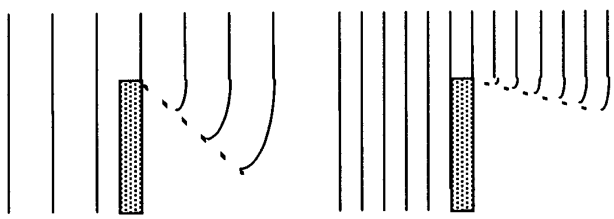
Refraction

When waves travel from one medium to another, they are **refracted**. This happens because the speed of the wave changes on entering the new medium. If the waves enter the medium at an angle to the normal, then their **direction** also changes. The greater the change in speed, the greater the change in direction.

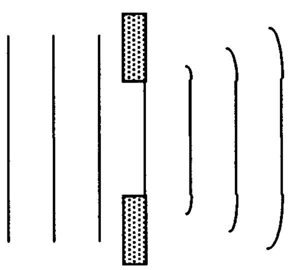
A **decrease in speed** means the direction moves **towards the normal**, and vice versa.

The **frequency** of the wave **never changes** and is **determined by the source**. It can only be altered at source.

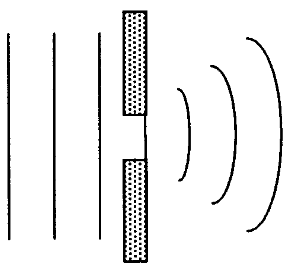
Diffraction



Larger wavelengths diffract more.



Gap larger than λ.



Gap similar to λ.

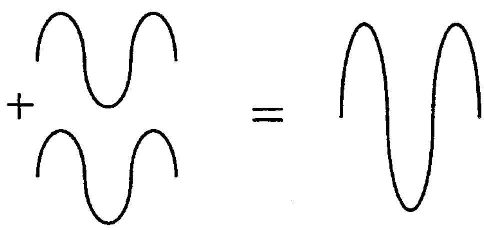
Interference

When two sets of waves meet, they combine to produce a new pattern. This pattern can vary depending on the original wave direction, wavelength, amplitude, etc. Waves can combine in one of two ways as illustrated below.

Constructive interference

Two sets of waves meet in **phase**.

Two crests meet or two troughs meet to produce a larger crest or trough.

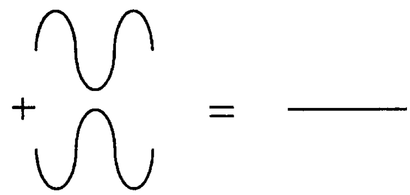


Destructive interference

Two sets of waves meet completely out of phase, i.e. 180° out of phase.

A crest meets a trough and combine to cancel each other out and produce no wave at that point.

If the waves are not of equal amplitude, then complete cancelling out does not occur.

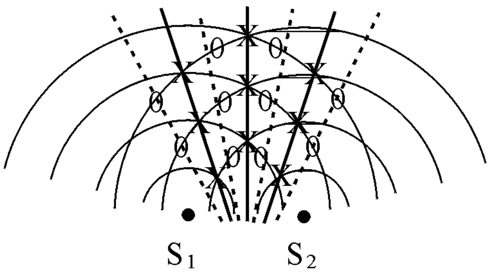


Coherent sources

Two sources are **coherent** if they have a constant phase difference. They will have the same frequency. They often have the same amplitude.

Interference of water waves

If two point sources produce two sets of circular waves, they will overlap and combine to produce an interference pattern.



The semicircular lines represent crests; the troughs are between the crests.

S_1 and S_2 are **coherent** point sources, i.e. the waves are produced by the same vibrator.

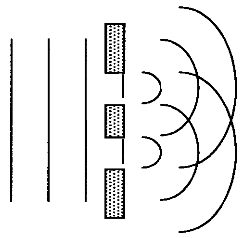
X = point of constructive interference.
O = point of destructive interference.
—— = line of constructive interference
- - - - = line of destructive interference.

The points of **constructive** interference form waves with larger amplitude and the points of **destructive** interference produce calm water.

The positions of constructive interference and destructive interference form alternate lines which spread out from between the sources. As you move across a line parallel to the sources, you will therefore encounter alternate large waves and calm water.

Interference from one set of waves

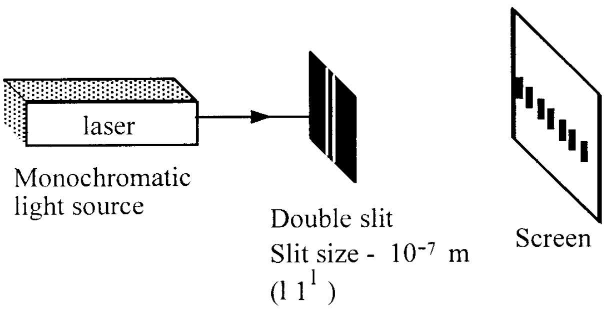
It is possible to produce interference from one source of waves by division of the wavefront. Plane waves are made to pass through two small gaps (similar in size to the wavelength) to produce two coherent sources of circular waves by diffraction. These will then interfere as before.



Interference of light

Two sources of coherent light are needed to produce an interference pattern. Two separate light sources such as lamps cannot be used to do this, as there is no guarantee that they will be coherent (same phase difference).

The two sources are created by producing two sets of waves from one monochromatic (single frequency) source using the principle above. A laser is a good source of this type of light.



Alternate series of light and dark lines (fringes).

Light fringe, arrive in phase, constructive.

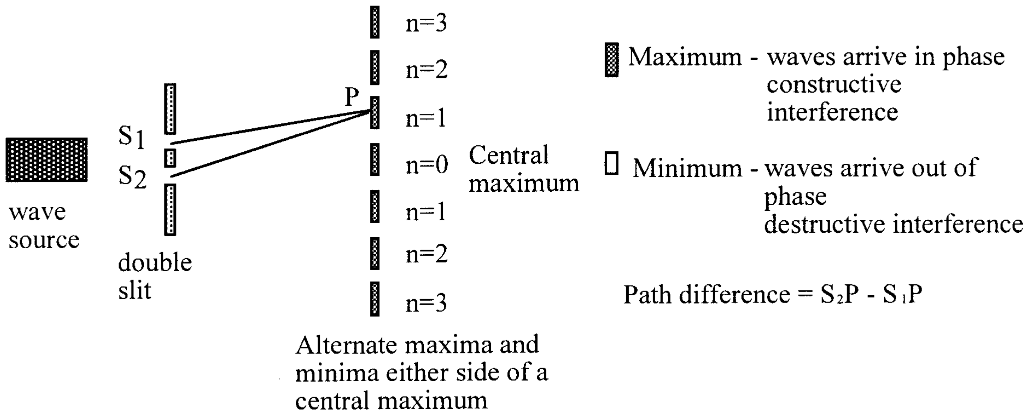
Dark fringe, arrive out of phase, destructive.

Interference can only be explained in terms of wave behaviour and as a result, **interference is taken as proof of wave motion**.

Historically, the original version of this experiment with two slits by Thomas Young proved that light did, in fact, travel in the form of waves.

Path difference and interference

An interference pattern is more easily explained in terms of path difference.
Consider an interference pattern produced by two coherent wave sources as below.



Take a point **P** in the interference pattern.

The central, or **zero order maximum** has **zero path difference**, as it is equidistant from each source.

As you move across the pattern away from the zero order, the **first order maximum** is reached. This is the next point where the waves arrive in phase; the waves here have a path difference of 1λ, the waves from one source have travelled 1λ further than the waves from the other source.

Similarly, the path difference to the second order maximum would be 2λ and so on.

The **zero order minimum**, the minimum next to the central maximum, is reached at the first point the waves arrive out of phase; the waves here have a path difference of $\frac{1}{2}\lambda$.

Similarly, the path difference to the next minimum would be $\frac{3}{2}\lambda$ and so on.

In general:

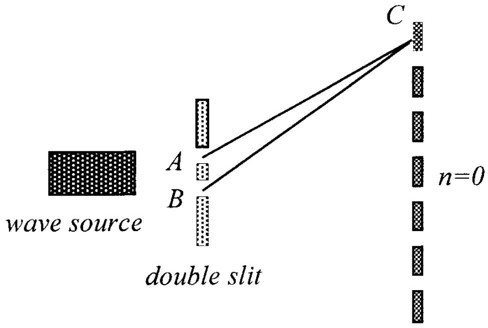
For a maximum path difference, $S_2P - S_1P = n\lambda$ Whole number of λ

For a minimum path difference, $S_2P - S_1P = (n + \frac{1}{2})\lambda$ Odd number of $\frac{1}{2}\lambda$.

The term 'order' for a maximum or minimum is simply the value of n in the above equations. For a maximum this is straightforward. When $n = 1$ we have the first maximum. However, for a minimum some care is required. The first minimum, the minimum next to the central bright band, is the 'zero order minimum' with $n = 0$. In most cases a simple diagram is useful.

Example

a) If distances *AC* and *BC* are 51 cm and 63 cm respectively, and point *C* is the third order maximum, determine the wavelength of the source.



Path difference *BC* – *AC* = 12 cm.
For third order maximum, path difference = 3λ.
3λ = 12 cm, so 1λ = 4 cm.

b) If the above source was replaced by another with wavelength 8 cm, what effect would be produced at point *C*?

Path difference *BC* – *AC* = 12 cm, as before.

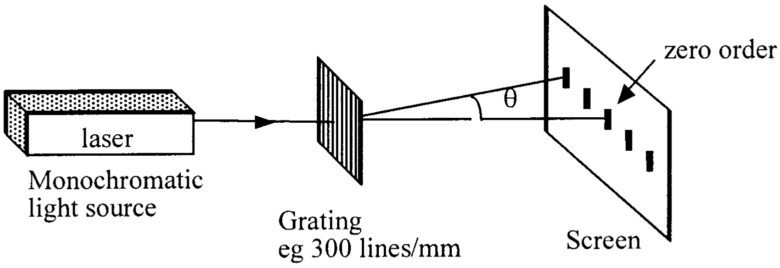
If λ = 8 cm: $\frac{12}{8} = \frac{3}{2}$ Therefore the path difference = $\frac{3}{2}$ or $1\frac{1}{2}\lambda$.

Point *C* would be the second minimum above the central bright band (or the 'first order minimum').

The pattern is now more spaced out.

The grating and monochromatic light

A grating consists of many equally spaced slits positioned extremely close together (e.g. 300 lines per mm). Light is diffracted through each slit and interference takes place in a similar fashion to the double slit. The advantage of the grating is that much more light is transmitted through and a clearer interference pattern is seen.



Grating equation

For a grating, $\boxed{n\lambda = d\sin\theta}$

Where: n = order of the maximum
λ = wavelength of light
d = separation of slits
θ = angle from zero order to nth maximum.
λ and d must be in same units.

If the above formula is rearranged to $\sin\theta = \dfrac{n\lambda}{d}$, then it can be seen that to increase θ, the separation of the maxima, you can:

- increase the wavelength, i.e. move from blue towards red light
- decrease the slit separation, i.e. have more lines per mm.

Also notice that moving the screen further away will also increase the distance between the maxima.

Example

A diffraction grating with 300 lines per mm is used to produce an interference pattern.
The second order maximum is obtained at a diffracted angle of 19°. Calculate the wavelength of the light.

Using the formula $n\lambda = d\sin\theta$ *:*

$$d = 1/300\text{mm} = 3.33 \text{ x } 10^{-3}\text{mm} = 3.33 \; x \; 10^{-6}\text{m}$$
$$n = 2$$
$$\theta = 19^{o}$$

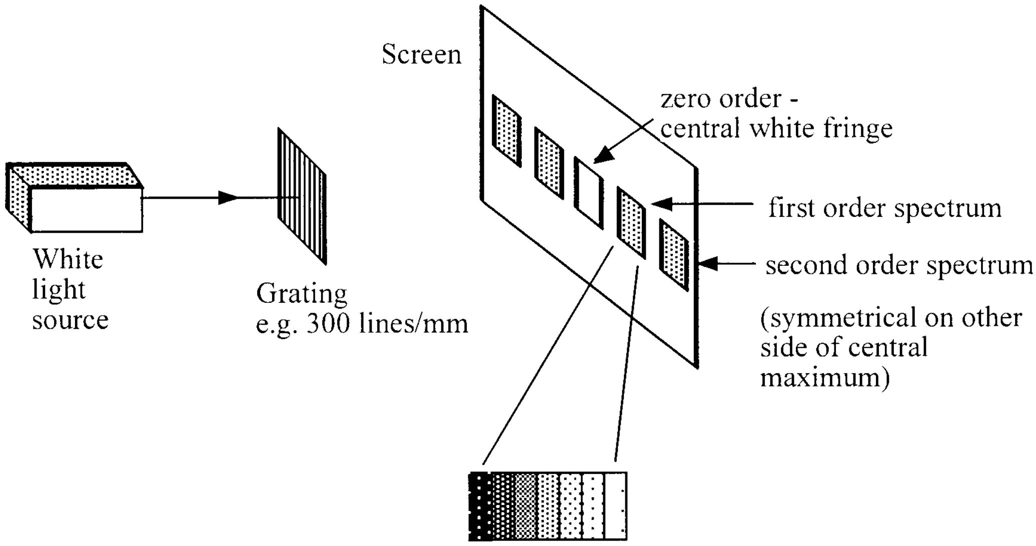
$$2\times\lambda = 3.33\times10^{-6}\sin 19^{\circ}$$
$$=5.4\times10^{-7}\text{ m or } 540\text{ nm}$$

Approximate values of wavelengths

Red	*700 mm*	=	7×10^{-7} *m*
Green	*540 nm*	=	5.4×10^{-7} *m*
Blue	*490 nm*	=	4.9×10^{-7} *m.*

Grating and white light

It is possible to use a grating to observe the interference pattern obtained from a white light source. Since white light consists of many different frequencies (wavelengths), the fringe pattern produced is not as simple as that obtained from monochromatic light.



Each fringe appears as a visible spectrum, apart from the central white fringe. Red is deviated the most, violet is deviated the least.

Explanation

The central fringe is white because at that position, the **path difference** for all wavelengths present is **zero**, therefore all wavelengths will arrive in phase. The central fringe is therefore the same colour as the source (in this case, white).

The first maximum occurs when the **path difference** is 1λ. Since blue light has a shorter wavelength than red light, the path difference will be smaller, so the blue maximum will appear closer to the centre. Each colour will produce a maximum in a slightly different position and so the colours spread out into a **spectrum**.

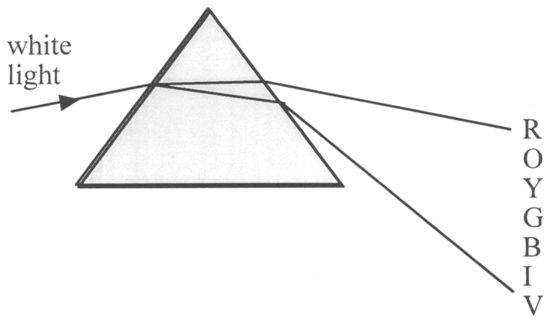
These effects can also be explained using the formula $d\sin\theta = n\lambda$.

If d and n are fixed, the angle θ depends on the wavelength. So, for any given fringe number, the red light, with a longer wavelength, will be seen at a greater angle than the blue light.

The higher order spectra overlap.

Comparing spectra from prisms and gratings

Prism



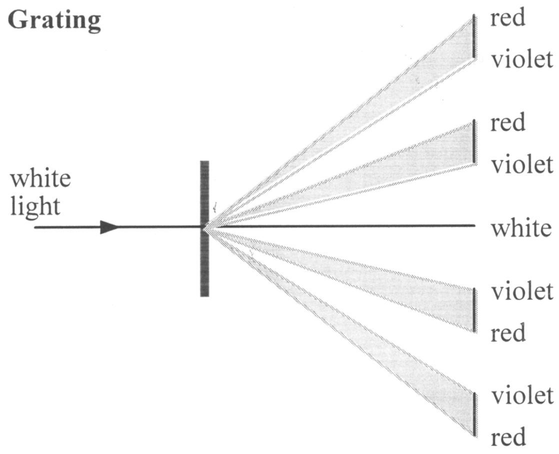
Only one spectrum produced.

Red deviated least, violet the most.

Bright images.

Usually less widely spaced (dispersed).

Grating



Many spectra produced, symmetrical about the central maximum.

Red deviated most, violet the least.

Less intense – energy divided between several spectra.

Usually more spread out.

Central image always the same colour as the source.

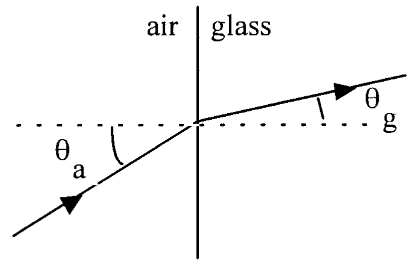
REFRACTION OF LIGHT

Refractive index

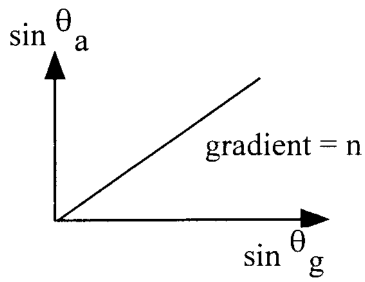
By varying the angle θ_a, a relationship between θ_a and θ_g can be found.

Experiment shows that $\frac{\sin\theta_a}{\sin\theta_g}$ is constant.

This constant is called the **reflective index** *n* of the medium.



$$\boxed{\frac{\sin\theta_a}{\sin\theta_g} = n}$$



The values given in data books are called **absolute refractive indices**. These are the ratios of the sine of the angle in a **vacuum**, not air, to the sine of the angle in the medium. However, for most practical purposes we can use air.

$$\boxed{\frac{\sin\theta_a}{\sin\theta_m} = n}$$

θ_a = angle in air measured relative to normal
θ_m = angle in medium measured relative to normal.

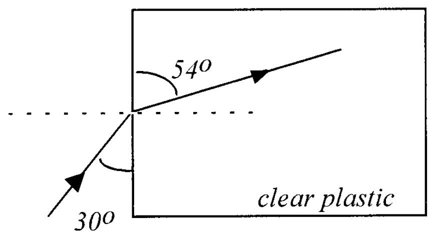
The refractive index measures the effect a medium has on light. The greater the refractive index, the greater the change in speed and direction.

The refractive index of a medium is the same whether light moves from air into the medium or vice versa.

The absolute refractive index is **always** a value greater than (or equal to) 1.

Example

Using information from the diagram, find the refractive index of the clear plastic.



All angles must be measured from the normal.

$\theta_a = 90 - 30 = 60^\circ$ $\theta_m = 90 - 54 = 36^\circ$

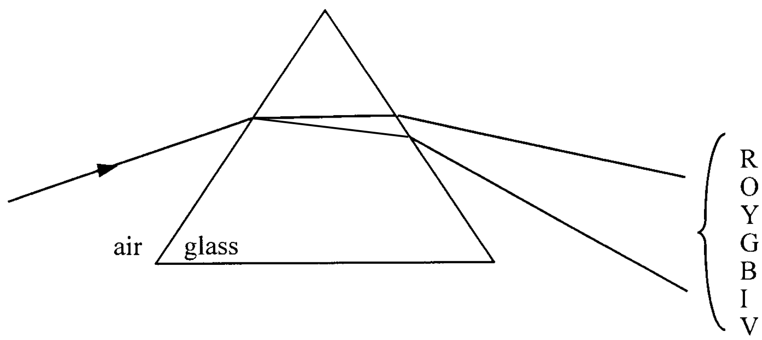
$$n = \frac{\sin\theta_a}{\sin\theta_m} = \frac{\sin 60}{\sin 36} = 1.47$$

Refractive index and frequency of light

The refractive index of a medium depends upon the frequency (colour) of the incident light.

When light enters a glass prism, it separates into its component colours and produces a spectrum. This happens because each colour (frequency) is refracted by a different amount.

Since violet is refracted more than red (i.e. it has changed speed and direction by a greater amount), it follows that the refractive index for violet light must be greater than the refractive index for red light.



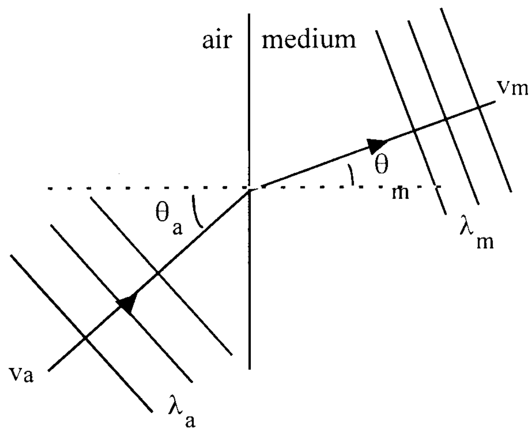
$$\boxed{n_{blue} > n_{red}}$$

Refractive index and relationship with v, λ and θ

$$\boxed{n = \frac{\sin\theta_a}{\sin\theta_m} = \frac{v_a}{v_m} = \frac{\lambda_a}{\lambda_m}}$$

In general, from medium 1 to medium 2:

$$\boxed{\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2}}$$



Example

Calculate the speed of light in glass of refractive index 1.50.

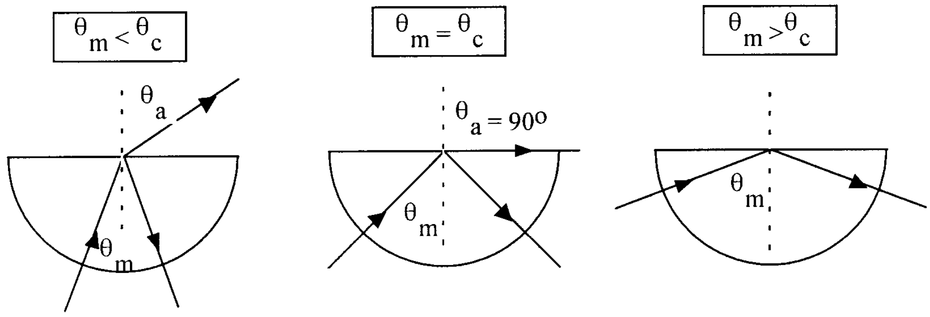
$\frac{v_a}{v_m} = n$ $\quad \frac{v_a}{v_m} = 1.50$ $\quad \frac{3 \times 10^8}{v_m} = 1.50$ $\quad v_m = 2 \times 10^8 \ m\ s^{-1}$

Critical angle and total internal reflection

When light travels from a medium of high refractive index to one of lower refractive index (e.g. glass into air), it bends away from the normal. If the angle within the medium θ_m is increased, a point is reached where the angle in θ_a becomes **90°**.

The angle in the medium which causes this is called the **critical angle**, θ_c.

If the angle in the medium is greater than the critical angle, then no light is refracted and **Total Internal Reflection** takes place within the medium.



Most of incident light refracted into air. Weak, partially reflected ray.

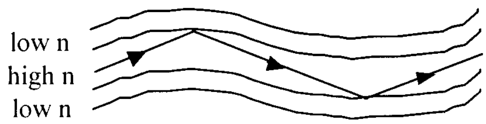
Light refracted into air at 90^o Partially reflected ray stronger.

No light refracted into air. All light reflected back into medium. **Total internal reflection** occurs.

Fibre-optics

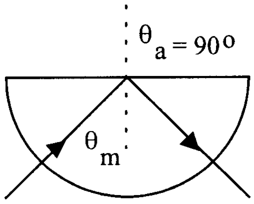
A thin glass fibre uses the principle of total internal reflection. The rays of light always strike the internal surface of the glass at an angle greater than the critical angle.

A commercial optical fibre has a fibre core of high refractive index surrounded by a thin, outer cladding of glass with lower refractive index than the core. This ensures that total internal reflection takes place.



Relationship between critical angle and refractive index

At the critical angle, $\theta_m = \theta_c$ and $\theta_a = 90°$



$$\frac{\sin\theta_a}{\sin\theta_m} = \frac{\sin 90^\circ}{\sin\theta_c} = \frac{1}{\sin\theta_c}$$

$$\boxed{n = \frac{1}{\sin\theta_c}}$$

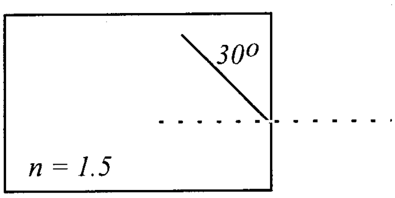
Total internal reflection is more likely to take place in a material with a small critical angle; therefore, it is desirable to use a medium of high refractive index when designing optical fibres.

Examples

1. *Calculate the critical angle for water of refractive index = 1.33.*

$$\sin\theta_c = \frac{1}{n} = \frac{1}{1.33} = 0.752 \qquad \theta_c = 49°$$

2. *A ray of light strikes the inside of a glass block as shown. Will the ray emerge from the glass?*



$$\sin\theta_c = \frac{1}{n} = \frac{1}{1.5}$$

$$\theta_c = 41.8°$$

The angle inside the glass is 60º, which is greater than 41.8º.
*Hence **total internal reflection** occurs.*

OPTOELECTRONICS AND SEMICONDUCTORS

Intensity of radiation

When radiation is incident on a surface, the intensity *I* is defined as the power per unit area.

$$\boxed{\underset{\mathrm{W\,m^{-2}}}{I} = \frac{P\ (\text{watts})}{A\ (\mathrm{m^2})}}$$

Intensity and distance

As you move further away from a point source, the intensity of radiation decreases. The relationship between intensity (*I*) and distance (*d*) can be shown to follow an **inverse square law**.

$$\boxed{I \propto \frac{1}{d^2}}$$

Inverse square law

$$\boxed{I_1 d_1^2 = I_2 d_2^2}$$

Intensity I_1 at distance d_1
Intensity I_2 at distance d_2

Note that a point source is one which emits light in all directions. Remember that intensity is **not** the same as brightness.

Light from a point source spreads out in all directions to illuminate the inside surface of a sphere.

Examples

1. *A lamp shines on a screen of area 2.5 m^2, which is 3 m away. The intensity at the screen is 0.01 W m^{-2}.*

   a) *Calculate the power of the incident beam.*

   $P = I \times A = 0.01 \times 2.5 = 0.025$ *W.*

   b) *If the screen is moved to a distance of 1.5 m from the lamp, what would the new intensity be?*

   $I_1 d_1^2 = I_2 d_2^2 \qquad 0.01 \times 9 = I_2 \times 2.25 \qquad I_2 = \dfrac{(0.01 \times 9)}{2.25} \qquad I_2 = 0.04\ \mathrm{W\,m^{-2}}$

2. *Calculate the intensity of a 100 W lamp at a distance of 2 m (the surface area of a sphere = 4 πr^2).*

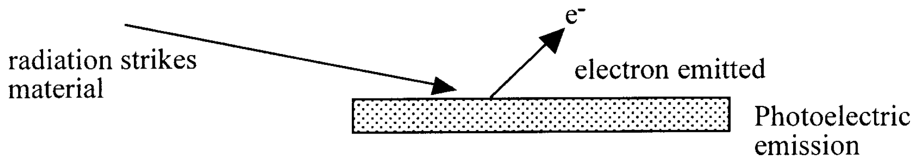
   Surface area of a sphere of radius 2 m is $A = 4\pi r^2 = 4\pi \times 4 = 50.27\ \mathrm{m^2}$.
   Power of lamp P = 100 W.

   Intensity $I = P/A = 100 / 50.27 = 1.99\ \mathrm{W\,m^{-2}}$.

Photoelectric emission

Sometimes when electromagnetic radiation above a certain frequency strikes a surface, electrons are emitted.

This can be used to detect radiation, and is the basis on which photodiodes, solar cells and light-dependent resistors operate.

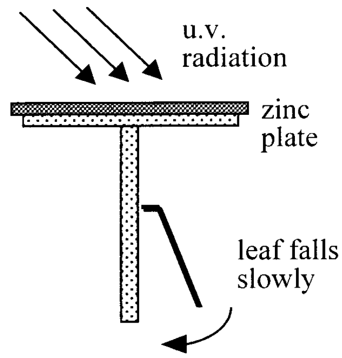


Photoelectric emission can be demonstrated by using a negatively-charged electroscope. When the zinc plate is exposed to u.v. radiation, the leaf falls.

If the intensity of the u.v. radiation is increased, the leaf will fall faster.

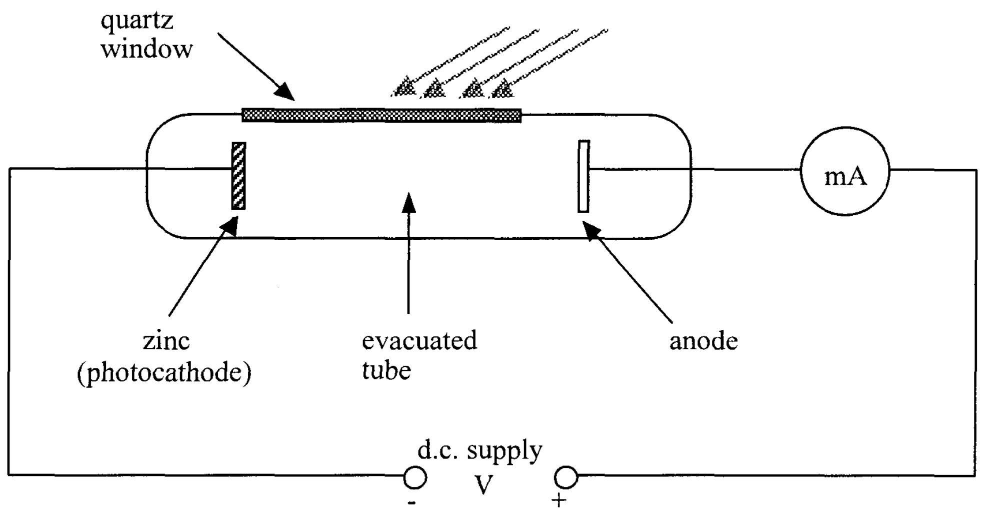
High intensity white light cannot eject electrons from zinc, while low intensity u.v. radiation can.

This has led to the development of a new theory in physics. This theory is called **quantum theory**.



Photoelectric current

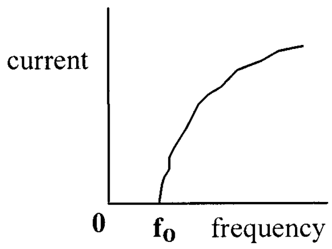
The following apparatus can be used to study photoelectric emission.



The u.v. radiation passes through the **quartz** window (a glass window would absorb the radiation) and strikes the photocathode 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 the milliammeter, called a **photoelectric current**.

Variation of frequency of the incident radiation

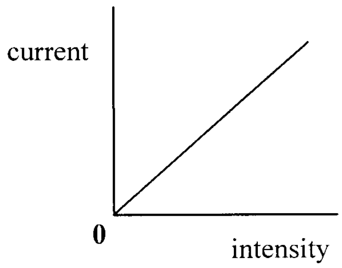
Below a certain frequency f_o, called the threshold frequency, there is no photoelectric emission and the photoelectric current will be zero. An increase in the intensity of the incident radiation, below f_o, will not cause photoelectric emission.



Variation of intensity of the incident radiation

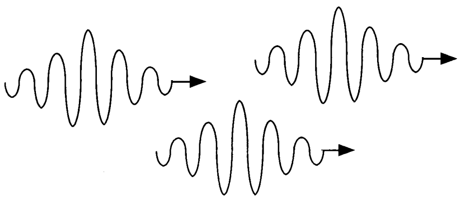
For a frequency greater than the threshold frequency, an increase in intensity (more photons) will produce an increase in photoelectric emission.

The photoelectric current is directly proportional to the intensity of the incident radiation.



Quantum theory of light (electromagnetic radiation)

The wave theory of light was unable to explain the photoelectric effect. This new quantum theory was proposed by Max Planck in 1905. His proposal was that light was not a continuous wave train but actually consisted of millions of wave packets or **quanta** called **photons**.



Photons

Continuous wave

Each photon has a frequency and wavelength associated with it just as a wave in the wave theory had. However, each photon has a particular energy that depends on its frequency, given by the equation below.

$\boxed{E = hf}$

where: E = energy of the photon (J)
f = frequency of the photon (Hz)
h = Planck's constant = 6.63×10^{-34} J s.

From this equation it can be seen that the energy of each photon is directly proportional to its frequency. The higher the frequency the greater the energy.

Intensity of photons

If N photons of frequency f are incident each second on each one square metre of a surface, then the energy per second (power) absorbed by the surface is:

$$P = \frac{E}{t} = \frac{\text{no of photons x energy of each photon}}{\text{time}} = \frac{N \text{ x } hf}{1} = Nhf$$

The **intensity** I at the surface is given by the power per square metre.

$$I = \frac{P}{A} = \frac{N \text{ x } hf}{1} = Nhf$$

$$\boxed{I = Nhf}$$

where: I = intensity in W m^{-2}
h = Planck's constant in J s
f = frequency in Hz
N = no of photons.

Threshold frequency and work function

In general there is a minimum frequency of electromagnetic radiation required in order to eject electrons from a particular metal. This is called the **threshold frequency,** f_o, and is dependent on the surface being irradiated.

The **minimum energy** required to release an electron from a surface is called the **work function**, E_o, of the surface.

$$\boxed{E_o = hf_o}$$

Such an electron would escape but would have no kinetic energy. If the energy of the incoming electron, $E = hf$, is greater than the work function, then the extra energy will appear as **kinetic energy** of the electron.

$$E_k = E - E_o$$

$$\boxed{E_k = hf - hf_o}$$

Example

The work function for a particular metal is stated as 5.10 × 10^{-19}J.

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

$$\textit{Minimum frequency} = f_o = \frac{E_o}{h} = \frac{5.10 \text{ x } 10^{-19}}{6.63 \text{ x } 10^{-34}} = 7.69 \text{ x } 10^{14}\,\text{Hz}$$

b) *If radiation of frequency 8.45 × 10^{14} Hz is incident on the same metal, calculate the maximum kinetic energy gained by each photoelectron.*

Photon energy $E = hf \quad = 6.63 \times 10^{-34} \times 8.45 \times 10^{14}$
$= 5.60 \times 10^{-19} J$

Kinetic energy $E_k \quad = E - E_o \quad = 5.60 \times 10^{-19} - 5.10 \times 10^{-19}$
$= 0.5 \times 10^{-19} J$
$= 5.0 \times 10^{-20} J$

Emission spectra

An emission spectrum is the range of colours given out (emitted) by a light source. There are two kinds of emission spectra: **continuous** spectra and **line** spectra. To view spectra produced by various sources, a spectroscope or spectrometer can be used.

Continuous spectra

If a beam of white light from a tungsten filament lamp, say, is passed through a prism or grating, then it splits up to form a continuous spectrum of light from red through to violet. All frequencies of radiation (colours) are present in the spectrum.

The continuous spectrum colours are red, orange, yellow, green, blue, indigo, violet.

Line spectra

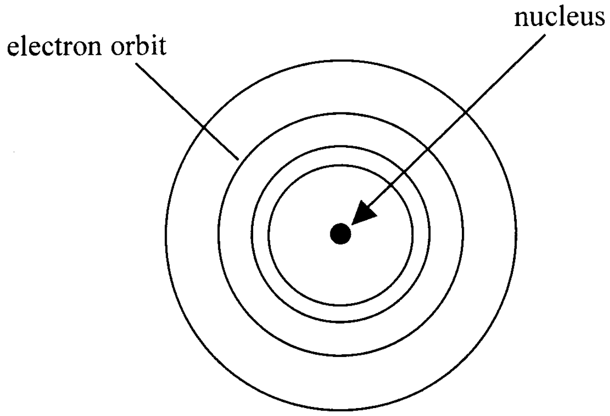
Some sources of light such as mercury and sodium vapour lamps do not produce continuous spectra when viewed through a spectroscope. They produce line spectra – coloured lines spaced out by different amounts. Only specific, well-defined frequencies of radiation (colours) are emitted.

For example, the spectrum of sodium has two, very bright, yellow lines close together as well as some other fainter lines. The yellow lines are known as the sodium doublet, or sodium D lines.

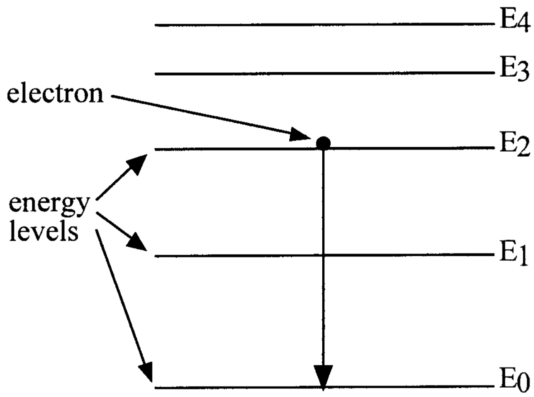
Explanation of emission spectra – the Bohr model

Using the ideas of Planck and Einstein, Neils Bohr was able to extend the Rutherford model of the atom. By suggesting that electrons are confined to certain orbits (or shells) around the nucleus, the Bohr model is able to explain emission spectra.

- The electrons have different energies in different orbits.
- There is a minimum number of electrons for each orbit.
- Electrons tend to occupy the lowest available energy levels (closest to the nucleus). They can move between levels, but cannot stop between them.



It is easier to represent the orbits in the form of an **energy level diagram**.



The lowest energy level E_o (or W_o) is called the **ground state**.

An electron which moves from its usual energy level to a higher energy level is said to be in an **excited** state.

An electron needs to absorb the correct amount of energy to move up one or more levels. It will later return to a lower level by emitting energy in the form of a **photon**.

The energy of the emitted photon is equal to the **difference in energy between the two levels**.

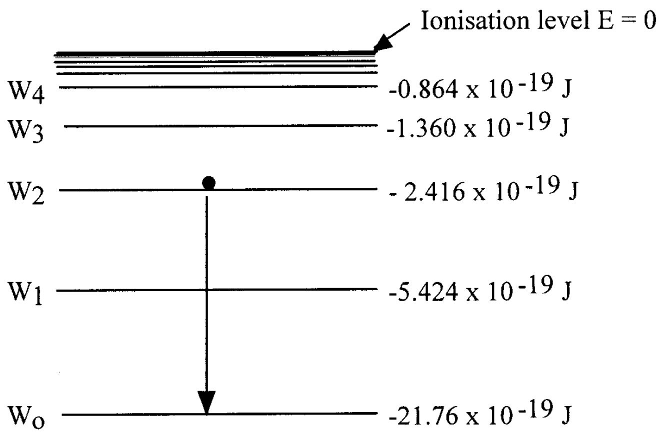
If the difference in energy levels is denoted as Δ**E**, then the frequency of the emitted photon will be expressed by the equation below.

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

Hz — f ; J — ΔE ; J s — h

The frequency of the emitted photon is therefore determined by the magnitude of the energy change.

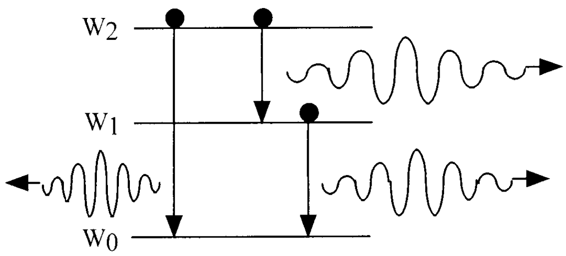
Energy levels in a hydrogen atom



A hydrogen atom has only one electron. If the electron is given enough energy, it can escape completely from the atom. The atom is then said to be in an **ionisation state**.

The energy of such an electron is said to be zero, since it is not connected to any atom. When an electron becomes attached to an atom, energy is given off so that the energy of the electron is reduced below zero and is, therefore, negative. Since the energy levels of an atom show the permitted electron energies, these energy levels must be negative also.

Imagine the electron had absorbed energy and jumped from energy level **0** to energy level **2**, as shown above. The electron can return from level **2** to level **0** directly, or via level **1**. Thus there are three possible frequencies of photon, giving three of the colours in the line spectrum.



Example

For the case of the transition from W_2 to W_1:

$\Delta E = W_2 - W_1$

$\Delta E = -2.416 – (-5424)) \times 10^{-19}$ J

$= 3.008 \times 10^{-19}$ J

$f = \Delta \mathbf{E}/h = \dfrac{3.008 \text{ x } 10^{-19}}{6.63 \text{ x } 10^{-34}}$

$= 4.537 \times 10^{14}$ Hz

This corresponds to a red/orange line in the emission spectrum of hydrogen.

More about spectra

Becomes each element has a different atomic structure, each element will produce a different line spectrum unique to that element. The line spectrum is a good way of identifying an element, a kind of 'atomic fingerprint'. Astronomers use this idea to identify elements in the spectrum of stars.

Most spectra contain bright lines and faint lines. This is because electrons sometimes favour particular energy levels. The transitions involving these energy levels will happen more often and hence lead to brighter lines in the emission spectrum, since more photons with that particular energy and frequency will be produced. How bright the line is depends on the number of photons emitted.

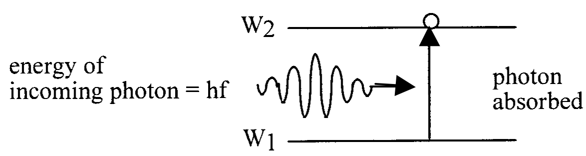
The energy to raise the electrons to the 'excited' higher levels can be provided in various ways:

- a high voltage, as in discharge tubes
- heat, as in filament lamps
- nuclear fusion, as in stars.

This theory applies only to **free** atoms. A free atom is one which is not affected by neighbouring atoms such as in a gas. In sources like filament lamps the atoms are not free and their electrons may be shared in bonding with other atoms. This results in an infinite number of possible transitions, giving an infinite number of lines, i.e. a continuous spectrum.

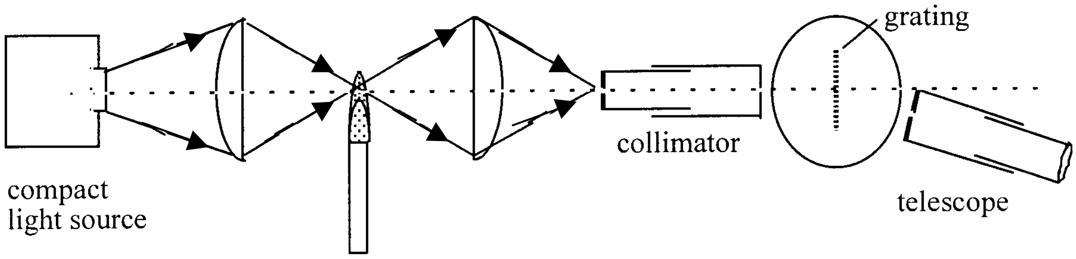
Absorption spectra

When light is passed through a medium containing a gas, then any photons of light which have the **same** frequency as the photons emitted to produce the emission spectrum of the gas, are absorbed by the gas. This is because the energy of the photons of light (hf) is the same as the energy difference required to cause an electron to be moved from the lower to the higher energy level. The energy is then absorbed by the electron and that photon is 'removed' from the incident light.



$$W_2 = W_1 + hf$$

In practice it may be difficult to produce a line absorption spectrum. The apparatus below shows how to produce an absorption spectrum for a sodium flame.



White light from the compact light source is passed through a large lens and brought to a focus within a sodium flame. The light then passes through another lens and is brought to focus on the slit of a spectrometer. Viewing the spectrum produced through the spectrometer reveals a continuous spectrum with two black lines in the yellow region. This is the absorption spectrum of sodium. The black lines correspond to the position of the sodium D lines in the sodium emission spectrum. These lines correspond to the frequencies of the photons **absorbed** by the electrons within the sodium flame.

The energy absorbed by the electrons within the sodium flame will be emitted again as a photon of the same energy and frequency as the one absorbed, but it is highly unlikely that it will be emitted in the same direction as the original photon. Therefore the spectrum viewed through the spectrometer will show black absorption lines corresponding to the absorbed frequency of radiation.

The atmosphere of the Sun contains sodium gas, therefore the spectrum of sunlight contains black absorption lines corresponding to the absorbed frequencies as above. The spectrum of sunlight is an absorption spectrum.

Spontaneous emission of radiation

We have seen that an electron will jump up to a different energy level if a photon is absorbed and then drop to a lower level again emitting a photon. The downwards transition of the electron may be **spontaneous**, i.e. not triggered in any way. This spontaneous emission is random. We can never tell exactly when one particular electron will drop, but we can find the time for a certain proportion of the electrons to undergo spontaneous emission.

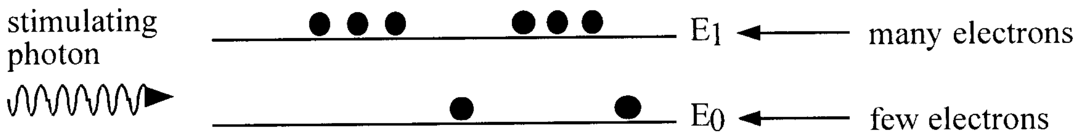
This is similar to the random process of radioactive decay.

Stimulated emission or radiation

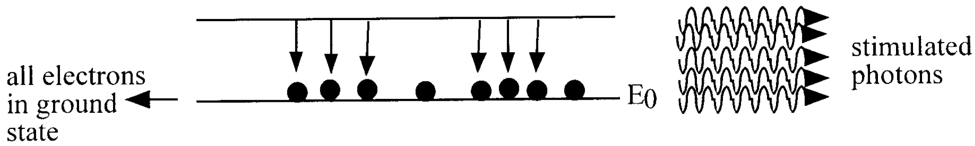
It is possible to **stimulate**, or trigger, the downwards transition of the electron. This can be achieved by passing a photon of **exactly** the right energy, equal to the energy difference between the two energy levels that the electron is to 'drop' between. The emitted photon will have the **same** frequency as the stimulating photon. The remarkable fact is that it is also **in phase** with the stimulating photon, and in exactly the same direction.

The laser

Consider a simplified energy level diagram with only two levels. If a material is to be used as a laser, the probability of spontaneous emission must be small, so electrons that are excited to energy level E_1 will stay there until they are stimulated by passing photons of the correct energy.



A few photons of energy E_1-E_0 are introduced. They will then stimulate the emission of identical photons, which in turn will lead to the stimulated emission of more. This ‘chain reaction’ results in an ‘avalanche’ of electrons stimulating the emission of many photons in a short and powerful pulse.

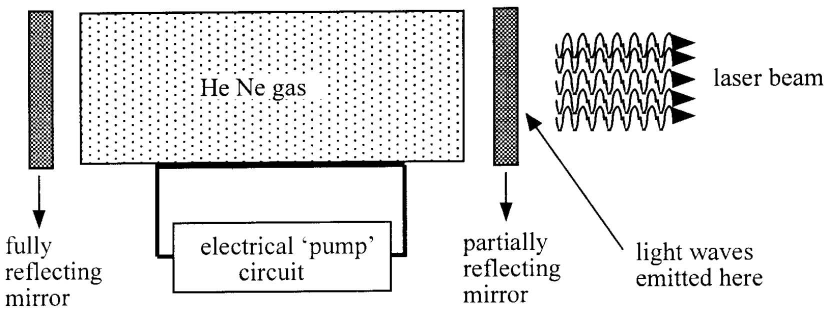


Thus the original small pulse of a few photons is amplified into a much more powerful pulse. Notice that the emitted photons are in phase and in the same direction.

This is called **L**ight **A**mplification by the **S**timulated **E**mission of **R**adiation (or LASER).

Construction of a laser

In the helium-neon gas laser a mixture of helium and neon gases is contained in a quartz tube. There are parallel mirrors, one at each end. They are designed to ‘trap’ most of the light inside the laser. One end has a perfect mirror and opposite it is one which will transmit about 1% of the light that strikes it and reflect the other 99% back into the gas mix. A radio frequency generator supplies the energy to ‘pump’ the electrons to the excited state. The mirrors are designed to keep most of the light in the tube since a high light intensity increases the probability of stimulated emission occurring. Each photon reflected back and forth along the tube will stimulate the emission of many more photons. The 1% that is transmitted through the one mirror constitutes the actual laser beam.



Laser light

Laser light has the following properties:

• **Monochromatic**	All the photons have the same frequency given by $f = \Delta E / h$.
• **Coherent**	All the photons are in phase.
• **Intense**	The power is concentrated in a small area. All the photons travel in phase, so will add constructively to give a greater amplitude. Even a laser beam of very low power, e.g. 0.1 mW can cause eye damage because of the high intensity.
• **An almost parallel beam**	The mirrors at each end are parallel. Any ray not parallel with the side if the laser will escape through the sides without being amplified.

Classifying materials

By considering their electrical properties, we can divide materials into three groups:

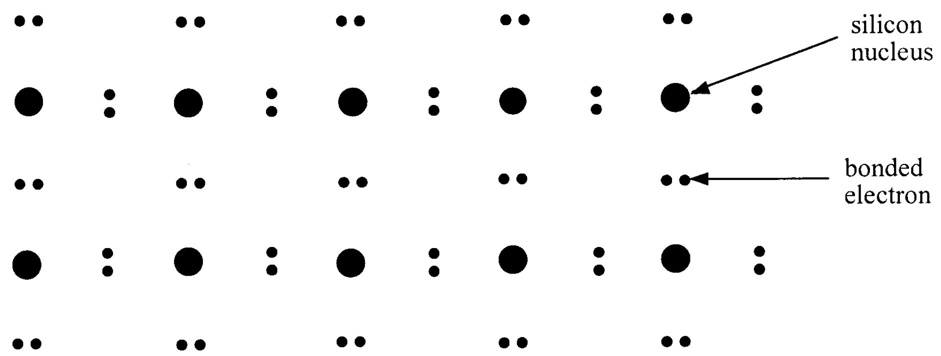
- **Conductors** — Materials with many free electrons. These elections can easily be made to flow through the material. For example, all metals, semi-metals like graphite, antimony and arsenic.
- **Semiconductors** — Materials which are insulators when pure, but will conduct when an impurity is added and/or in response to light, heat, voltage, etc. For example, elements like silicon (Si), germanium (Ge), selenium (Se); compounds like gallium arsenide (GaAs) and indium antimonide (InSb).
- **Insulators** — Materials that have very few free electrons, which cannot move easily. For example, plastic, glass and wood.

Semiconductors

The electrical properties of semiconductors make them very important in electronic devices like transistors, diodes and light-dependent resistors (LDRs). In such devices the electrical properties are dramatically changed by the addition of very small amounts of impurities. The process of adding impurities to these semiconductors is known as **doping**. The development of doped semiconductors in the 1950s led to the invention of the transistor and the start of the 'solid state' revolution that transformed the whole face of electronics.

Bonding in semiconductors

The most commonly used semiconductors are silicon and germanium. Both these materials have a valency of four, that is they have four outer electrons available for bonding. In a pure crystal, each atom is bonded covalently to another four atoms. All of its outer electrons are bonded and therefore there are few free electrons available to conduct. This makes the resistance very large.

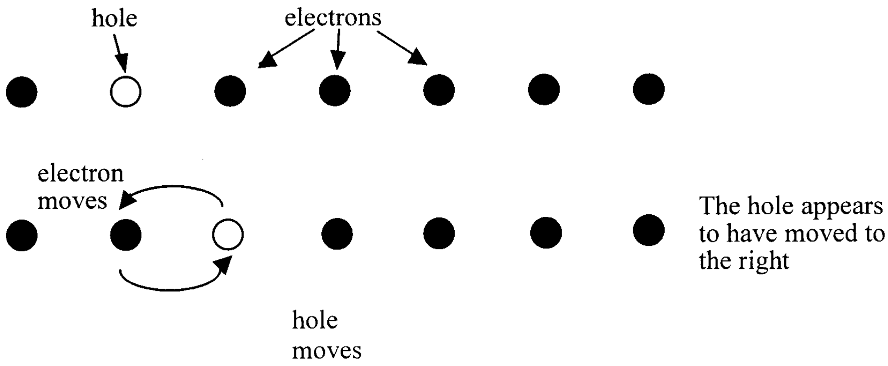


The few electrons that are available come from imperfections in the crystal lattice and thermal ionisation due to heating. A higher temperature will thus result in more free electrons, increasing the conductivity and decreasing the resistance, as in a thermistor.

Holes

When an electron leaves its position in the crystal lattice, there is a space left behind that is positively charged. This lack of an electron is called a **positive hole**.

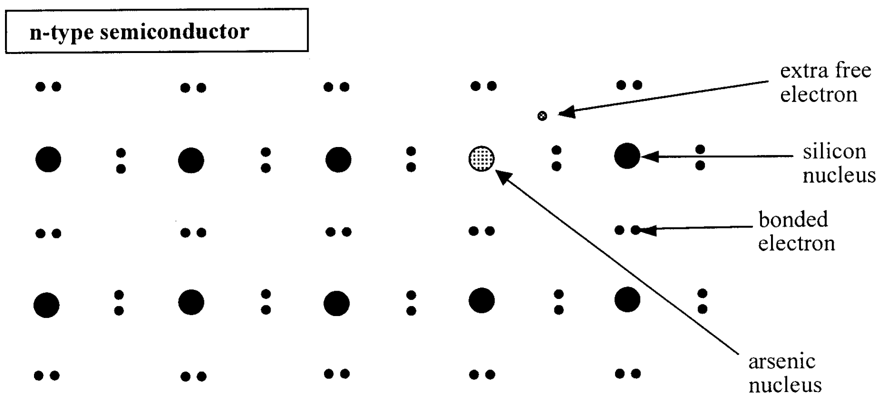
This hole may be filled by an electron from a neighbouring atom, which will in turn leave a hole there. Although it is technically the electron that moves, the effect is the same as if it was the hole that moved through the crystal lattice. The hole can then be thought of as the charge carrier.



In an undoped semiconductor, the number of holes is equal to the number of electrons. Current consists of drifting electrons in one direction and drifting holes in the other.

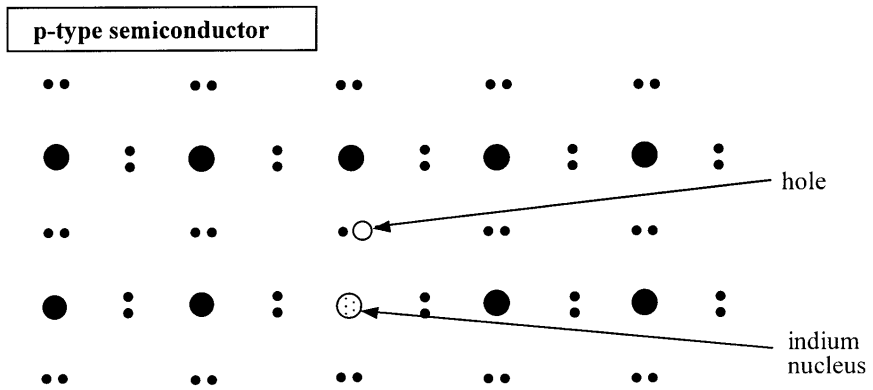
Doping

If an impurity such as arsenic (As), which has **five** outer electrons, is present in the crystal lattice, then four of its electrons will be used in bonding with the silicon. The fifth will be free to move about and conduct. Since the ability of the crystal to conduct is increased, the resistance of the semiconductor is therefore reduced. The addition of an impurity like this is called **doping**.



This type of semiconductor is called **n-type**, since most conduction is by the movement of free electrons, which are, of course, **negatively charged**.

The semiconductor may also be doped with an element like indium (In), which has only three outer electrons. This produces a hole in the crystal lattice, where an electron is 'missing'.



An electron from the next atom can move into the hole created as described previously. Conduction can thus take place by the movement of positive holes. This is called a **p-type** semiconductor, as most conduction takes place by the movement of **positively charged** 'holes'.

Notes on doping

- The doping material cannot simply be added to the semiconductor crystal. It has to be grown into the lattice when the crystal is grown so that it becomes part of the atomic lattice.

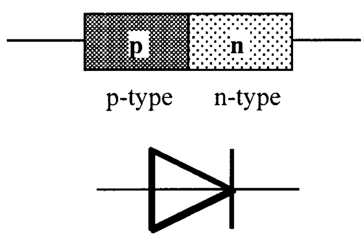
- The quantity of impurity is extremely small; it may be as low as one atom in a million.

- Although p-type and n-type semiconductors have different charge carriers, they are still both **overall neutral** (just as metal can conduct but is normally neutral).

- Each type of semiconductor will still have small amounts of additional free electrons due to thermal ionisation.

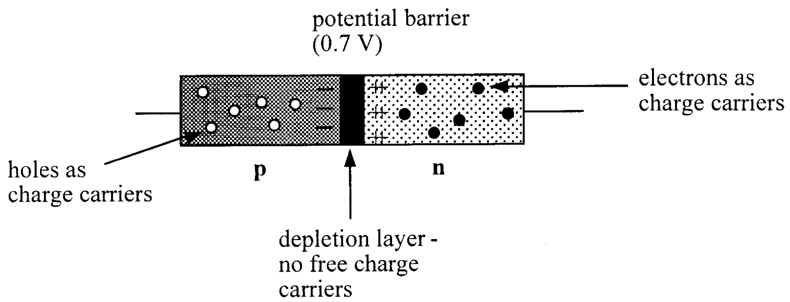
The p-n junction diode

When a semiconductor is grown so that one half is p-type and the other half is n-type, the product is called a **p-n junction diode**.



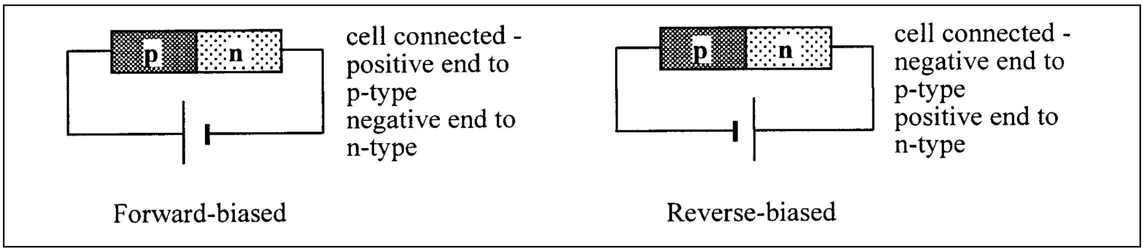
circuit symbol

Some of the free electrons from the n-type material diffuse across the junction and fill some of the holes in the p-type. This can also be thought of as holes moving in the opposite direction to be filled by electrons. Because the n-type has lost electrons, it becomes positively charged near the junction. The p-type, having gained electrons, will become negatively charged. There will be a small voltage, a potential barrier (about 0.7 V in silicon), across the junction due to this charge separation. This voltage will tend to oppose any further movement of charge. The region around the junction has lost virtually all its free charge carriers. This region is called the **depletion layer**.

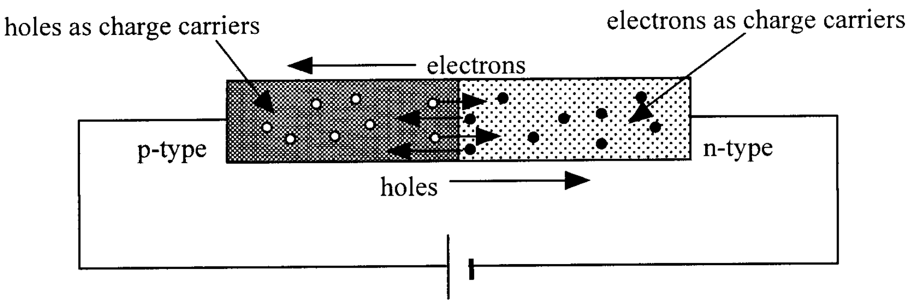


Biasing the diode

To bias a semiconductor device means to apply a voltage to it.
A diode may be biased in two ways.

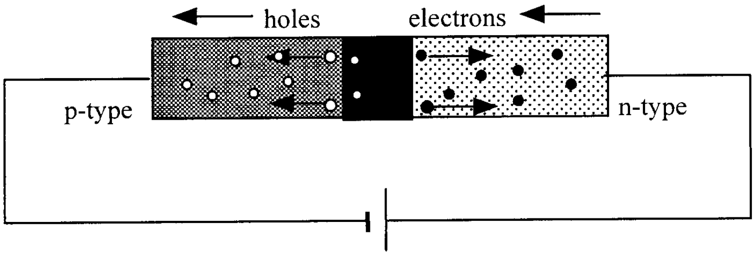


The forward-based diode



Electrons from the n-type will be given enough energy from the battery to overcome the depletion layer p.d. (the potential barrier) and flow through the junction and round the above circuit in an anti-clockwise direction. This movement will result in a similar movement of holes in the clockwise direction. The diode conducts because the depletion layer has been removed.

The reverse-biased diode

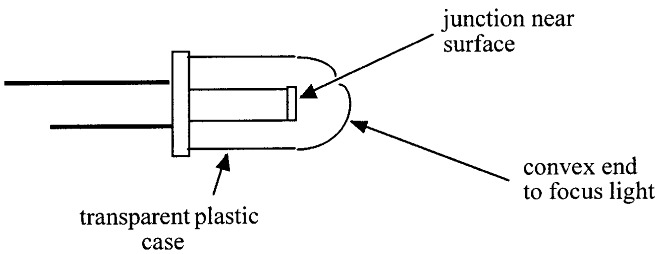


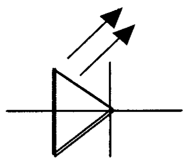
In the reverse-biased diode the applied potential causes the depletion layer to increase in depth, increasing the size of the potential barrier, making the diode even less likely to conduct.

Note

A graph of the variation of current with p.d. across a p-n junction is obtained in Activity 11.

The light-emitting diode



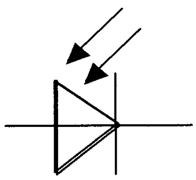


circuit symbol

We have seen that in a forward-biased p-n junction diode, holes and electrons pass through the junction in opposite directions. Sometimes holes and electrons will meet and recombine. When this happens, energy is emitted in the form of a photon. For each recombination of electron and hole, one photon of radiation is emitted. In most semiconductors this takes the form of heat, resulting in a temperature rise. In some semiconductors such as gallium arsenic phosphide, however, the energy is emitted as light. If the junction is close to the surface of the material, this light may be able to escape. This makes what we call a **Light Emitting Diode (LED)**. The colour of the emitted light (red, yellow, green, blue) depends on the relative quantities of the three constituent materials.

The photodiode

A p-n junction in a transparent coating will **react** to light. This photodiode can be used in two modes.

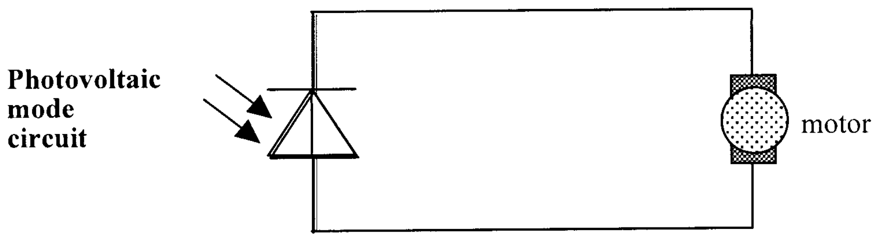


circuit symbol

Photovoltaic mode

In this mode the diode has **no** bias voltage applied. Photons that are incident on the junction have their energy absorbed, freeing electrons and creating electron-hole pairs. A voltage is generated by the separation of the electron and hole. More intense light (more photons) will lead to more electron-hole pairs being produced and therefore a higher voltage. In fact the voltage is proportional to the light intensity.

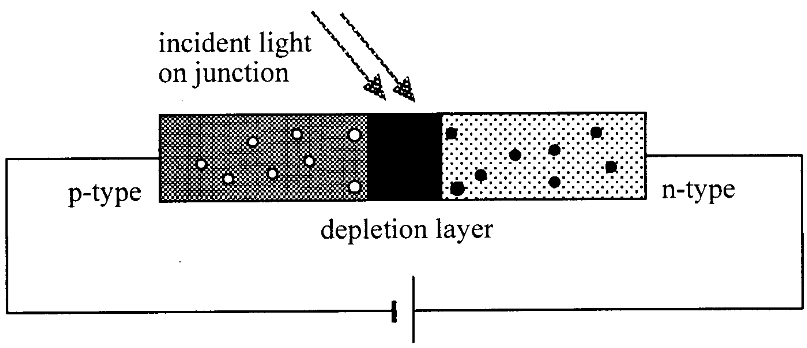
In this mode, the photodiode will supply power to a load, e.g. a motor. This is the basis of **solar cells**.



It is interesting to note that in this mode, the photodiode acts like a LED in reverse.

Photoconductive mode

In this mode the photodiode is connected in **reverse bias**. As we have seen earlier in the notes, we would not expect this to conduct. If it is kept dark, it acts just like an ordinary reverse-biased p-n junction and will not conduct. However, light shining on the junction will release electrons and create electron-hole pairs as above. This will provide a number of **free charge carriers** in the depletion layer, decreasing the resistance and enabling a current to flow. A greater intensity of light will lead to more free charge carriers and therefore less resistance. The photodiode acts as a **light dependent resistor (LDR)**.



The electron-hole pairs created in a photodiode recombine very rapidly; therefore, a photodiode reacts very quickly to changes in light intensity, which makes it very useful for detecting rapid light level changes, e.g. speed measurement, fibre-optic communication.

Summary of semiconductor devices

- **p-n junction diode** forward bias – conducts
  reverse bias – does not conduct.

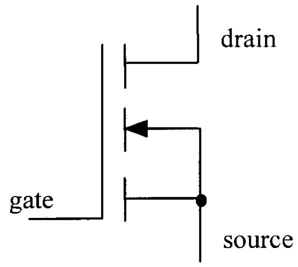
- **LED** forward bias – conducts and emits light
  reverse bias – does not conduct, so does not emit light.

- **photodiode** no bias - photovoltaic mode – acts like a solar cell
  reverse bias – photoconductive mode – acts like an LDR.

Metal oxide semiconductor field effect transistors (MOSFETs)

Circuit symbol

This is the circuit symbol for an n-channel enhancement MOSFET



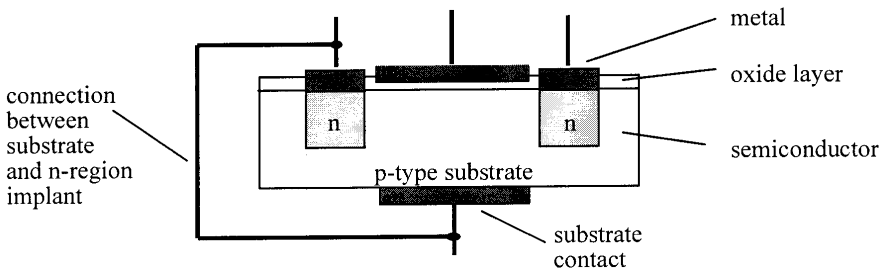
The three terminals are called the **gate**, the **source** and the **drain**. The broken line in the symbol indicates that there is normally no conducting path between the source and the drain.

How MOSFETs are made

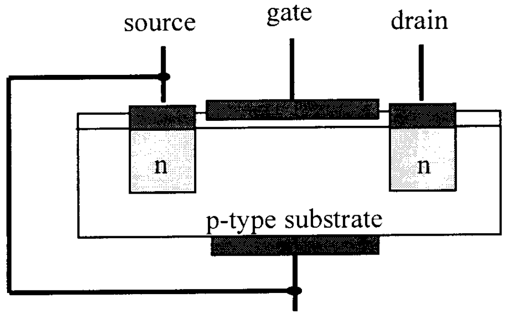
The starting point for a MOSFET is a slab of p-type semiconductor. This is called the **substrate**. Using the process of diffusion, two n-type regions are implanted at either end. These are the n-region **implants**.

A thin layer of insulating oxide is now deposited on top of the substrate and implants. This is the **oxide layer**. In order to make contact with the n-region implants, some of the oxide layer is etched away. Metal contacts are made to the n-region implants and to the insulating oxide layer between them. These are the metal contacts. The thickness of the oxide layer under the metal contact is made very thin.

Often there is a contact made between the substrate and one of the n-region implants. This connection can be made either internally or externally. In the Higher Physics course, this connection will always be shown.

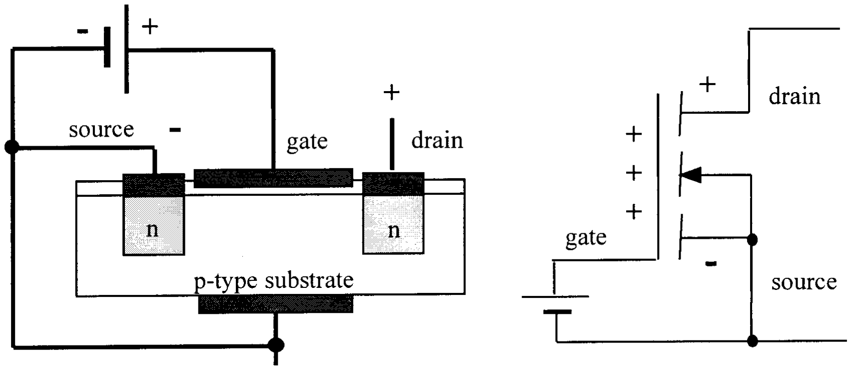


The terminal connected to the n-region and substrate is the **source**.
The terminal insulated from the substrate by the oxide layer is the **gate**.
The other n-region implant contact is the **drain**.



Switching the MOSFET on

We can consider what happens when a potential difference is applied between the gate and the source (the potential of the gate becomes positive).

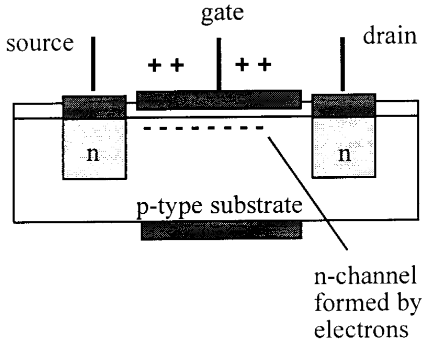


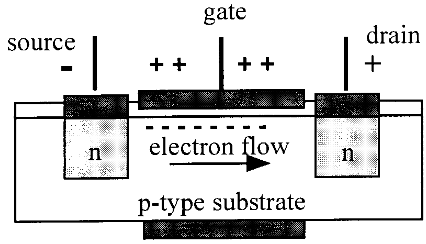
The positive potential on the gate causes a conducting layer of electrons to form below the gate just beneath the insulator.

This channel is called an **n-channel** (since it is formed by electrons).

When the channel is formed, this allows the possibility of a current between the source and the drain. If there is a potential difference between the drain and source, then current will flow as shown below.

The arrow on the MOSFET circuit symbol indicates which type of channel is formed. When it points inwards, towards the gate, a channel of negative electrons is formed (n-channel). When it points outwards away from the gate, a channel of positive charge carriers is formed (p-channel). (For this course, the arrow will always point inwards, since only n-channel MOSFETs will be used).





Current flows between source and drain when the channel is formed.

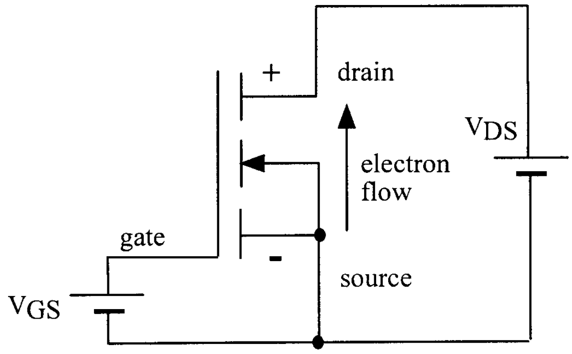
MOSFET circuits (n-channel enhancement MOSFETs)

The simple circuit below allows us to define the terms used in MOSFET circuits.

The p.d. across the source and drain is V_{DS} (note how the drain is always more positive than the source).

The p.d. across the source and gate is V_{GS} (note how the gate is more positive than the source).

The current in the drain-source circuit is I_D, which is called the drain current.



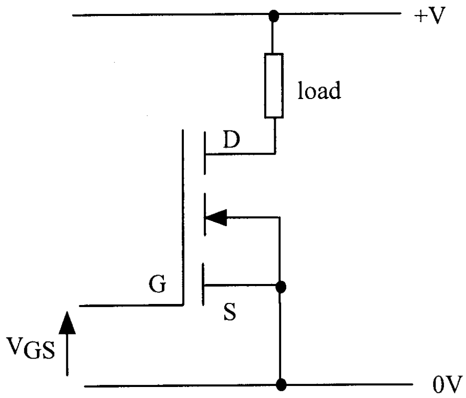
Note:

- V_{GS} has a minimum value called the threshold voltage – about 2 V.
- If V_{GS} is below this value, then the transistor will not conduct and I_D is zero.
- When V_{GS} greater than the threshold voltage is applied, I_D is now non-zero due to the presence of V_{DS}.
- If V_{DS} is increased, I_D increases (so long as V_{GS} is kept the same).

The MOSFET as a switch

The simplest application of a MOSFET is to switch current in a load. The load resistor could be any device: a lamp, buzzer, motor, heater, etc.

A p.d. greater than the threshold voltage (usually about 2V) applied to the gate (V_{GS}) will turn ON the MOSFET and there will be a drain current I_D in the load resistor.



The MOSFET as an amplifier

Another application of an n-channel MOSFET is an amplifier for analogue signals, e.g. audio signals. A MOSFET amplifier has very high input resistance.

MOSFET devices are used extensively in analogue and digital electronics.

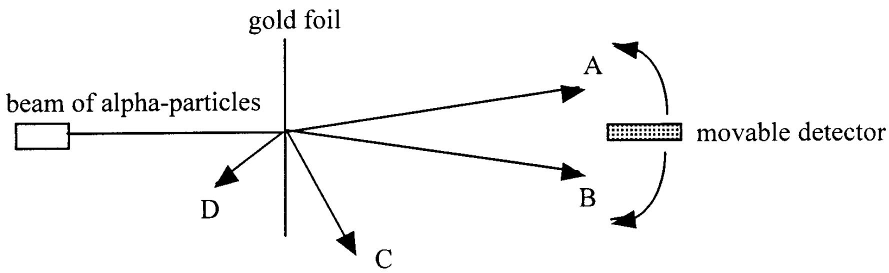
NUCLEAR REACTIONS

The Rutherford Atom

At the turn of the century, matter was thought to be made from small indivisible particles called atoms. There was, however, evidence to suggest that there were even smaller particles, and an early model of the atom was the 'plum pudding' model. This model had to be revised in order to explain the results of an important experiment carried out by Geiger and Marsden under the direction of Rutherford.

Rutherford's Scattering Experiment

Alpha particles were fired at a thin gold foil in a **vacuum**. The various angles through which the particles were deflected were measured.



The observations were:

- most of the alpha particles passed straight through the foil, with little or no deflection, being detected between positions A and B
- a few particles were deflected through large angles, e.g. to position C, and a very small number were even deflected backwards, e.g. to position D.

The explanations suggested a **nuclear atom**.

- The fact that most of the particles passed straight through the foil, which was at least 100 atoms thick, implied that the **atom must be mostly empty space**.
- In order to produce the large deflections at C and D, the alpha particles must be colliding with something **very small, of large mass** and positively charged.

Rutherford suggested that the atom consisted of a small positive nucleus that contains most of the mass of the atom and which is small compared to the size of the atom. The remaining space is taken up by the electrons (negative particles) orbiting the nucleus. (The diameter of the atom is about 10,000 times the diameter of the nucleus.)

Structure of the nucleus

It is now known that the nucleus consists of **protons**, with mass number 1 and charge +1, and **neutrons** with mass number 1 and charge 0. Protons and neutrons are collectively known as **nucleons**.

- The total number of protons and neutrons in the nucleus is called the **mass number A**.
- The number of protons in the nucleus is called the **atomic number Z**.
- In a neutral atom the number of protons equals the number of electrons.

The mass numbers, charges and symbols for protons, neutrons and electrons are given below.

Particle	Mass number	Charge	Symbol
Proton	1	+1	$\frac{1}{1}p$
Neutron	1	0	$\frac{1}{1}n$
Electron	0*	-1	$\frac{1}{-1}e$

* mass of electron = 1/1840 mass of proton.

Each **element** in the periodic table has a different atomic number and is identified by that number. It is possible to have different versions of the same element, called **isotopes**. An isotope of a atom has the same number of protons but a **different** number of neutrons, i.e. the same atomic number but a different mass number.

An isotope is identified by specifying its chemical symbol along with its atomic and mass numbers. For example:

Carbon-12 $^{12}_{6}C$ contains 6 protons and 6 neutrons (12 – 6)

Carbon-14 $^{14}_{6}C$ contains 6 protons and 8 neutrons (14 – 6)

Radioactive decay

Many nuclei are unstable. In order to achieve stability, they can emit nuclear radiation: alpha, beta or gamma. Such unstable nuclei are called **radioisotopes** or **radionuclides**.

The process of emitting radiation is called **decay**.

The following is a summary of the nature and symbols for the three types of nuclear radiation. Notice that gamma radiation has zero mass and zero charge.

Radiation	Nature	Symbol
Alpha particle	Helium nucleus	$^{4}_{2}He$ α
Beta particle	Fast electron	$^{0}_{-1}e$ β
Gamma ray	High frequency electromagnetic wave	γ

Representation of decay by symbols and equations

In the following equations, both mass number and atomic number are **conserved**, i.e. the totals are the same before and after the decay.

The original radionuclide is called the **parent** and the new radionuclide produced after decay is called the **daughter product** (sometimes this may go on to decay further).

Alpha decay

Uranium 238 decays by alpha emission to give Thorium 234.

$$^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}$$

Mass number decreases by 4, atomic number decreases by 2 (due to loss of 2 protons and 2 neutrons).

Beta decay

Lead 210 decays by beta emission to give Bismuth 210.

$$^{210}_{82}\mathrm{Pb} \rightarrow {}^{210}_{83}\mathrm{Bi} + {}^{0}_{-1}\mathrm{e}$$

Mass number is unchanged, atomic number increases by 1 (in beta decay a neutron in the nucleus changes into a proton and an electron. This electron is the emitted beta particle.)

Gamma decay

Only energy is emitted and the daughter product is the same as the parent.

Example

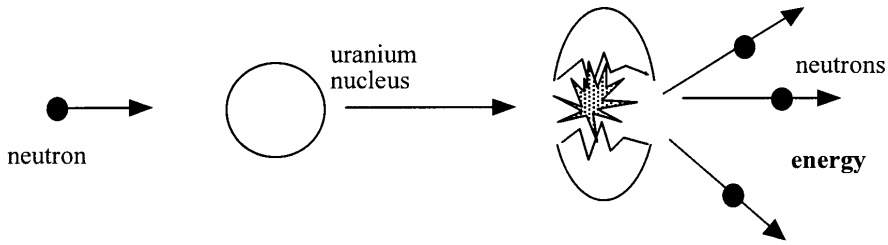
Thorium 230 decays into Radon. State the name of the particle emitted and give the equation for this decay. (Atomic number of Thorium is 90 and that of Radon is 88).

$$^{230}_{90}\mathrm{Th} \rightarrow {}^{226}_{88}\mathrm{Ra} + {}^{4}_{2}\alpha$$

Because the atomic number of Radon is less than Thorium, an alpha particle must have been emitted.

Nuclear fission

Fission occurs when a heavy nucleus disintegrates, forming two nuclei of smaller mass number. Fission can occur spontaneously, but it is usually induced by **neutron bombardment**.



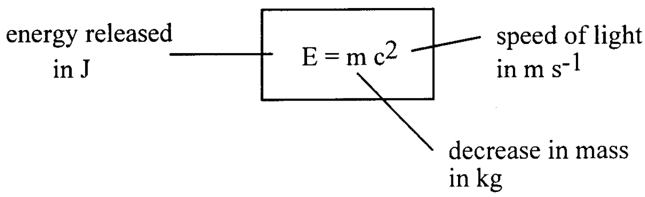
$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{92}_{36}Kr + ^{141}_{56}Ba + 3\,^{1}_{0}n + \text{energy}$$

Mass number and atomic number are both conserved during this reaction.

Even though the mass number is conserved, when the masses before and after the fission are compared accurately, there is a mass difference. The total mass before fission is greater than the total mass of the products.

Einstein suggested that mass was a form of energy, and that when there was a decrease in mass, an equivalent amount of energy was produced.

Einstein's famous equation shows how mass and energy are related:



In fission reactions, the energy released is carried away as **kinetic energy** of the fission products.

Fission reactions take place in **nuclear reactors**. The neutrons released are fast moving. A moderator, e.g. graphite, is used to slow them down and increase the chance of further fissions occurring. These slow (thermal) neutrons cause a chain reaction so that more fissions occur. Control rods, e.g. boron, absorb some of the slow neutrons and keep the chain reaction under control. The kinetic energy of the fission products converts to heat in the reactor core.

Example

Calculate the energy released during this fission reaction.

$$^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \rightarrow ^{137}_{56}\mathrm{Ba} + ^{97}_{42}\mathrm{Mo} + 2\ ^{1}_{0}\mathrm{n} + \text{energy}$$

Mass before fission (kg)		*Mass after fission (kg)*	
U	390.2×10^{-27}	*Ba*	227.3×10^{-27}
n	1.675×10^{-27}	*Mo*	160.9×10^{-27}
		2n	3.350×10^{-27}
	391.875×10^{-27}		391.550×10^{-27}

Decrease in mass $= (391.875 - 391.550) \times 10^{-27} = 0.325 \times 10^{-27}$ *kg*

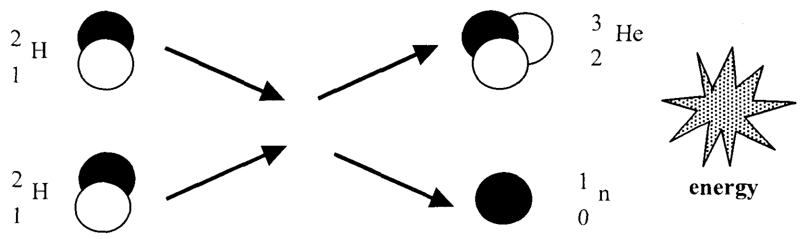
Energy released during this fission reaction, using $E = mc^2$

$$E = 3.25 \times 10^{-28} \times (3 \times 10^{8})^2 = 2.9 \times 10^{-11}\ J$$

This is the energy released by fission of a single nucleus.

Nuclear fusion

Fusion occurs when two light nuclei combine to form a nucleus of larger mass number, e.g. the fusion of two deuterium nuclei (an isotope of hydrogen) to form helium.



$$^{2}_{1}\mathrm{H} + ^{2}_{1}\mathrm{H} \longrightarrow ^{3}_{2}\mathrm{He} + ^{1}_{0}\mathrm{n} + \text{energy}$$

Once again, there is a decrease in mass in the fusion process and the energy released is produced as kinetic energy of the fusion products.

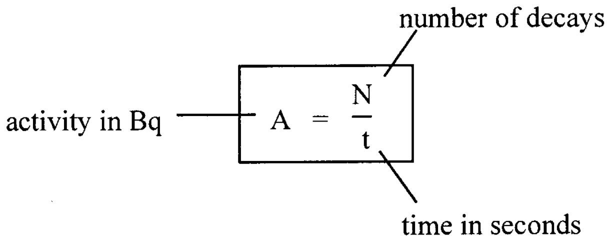
The energy released by the sun and other stars is produced by nuclear fusion.

DOSIMETRY AND SAFETY

Activity

The activity, A, of a source of radiation is the number of nuclei *N* which decay in one second.

1 becquerel (Bq) = 1 decay per second.



Examples of activity values:

- Sea water = approx 11 Bq per litre.
- 1 gram of natural uranium = 12kBq from U-238 and 0.56 kBq from U-235.

For any given nuclide, the activity is not constant, but depends on the quantity of nuclide present. For example:

- 1 g of pure radium = 3.7×10^{10} Bq.
- 2 g of pure radium = 7.4×10^{10} Bq, and so on.

Also, activity is not constant for a given nuclide – not every 1g of pure radium would have the above activity – it varies with time as decay occurs.

Half-life

The quantity, which is constant, is the **half-life**. The half-life is the time taken for half the radioactive nuclei present to decay.

If at any time there are *x* radioactive nuclei present, then:

after 1 half-life there will be $x/2$ nuclei left
after two half-lives there will be $x/4$ nuclei left
after *n* half-lives there will be $x/2^n$ nuclei left.

Half-life values vary widely.

Radionuclide	Half-life
Tellurium-99	6 hours
Iodine-131	8 days
Cobalt-60	5.24 years
Uranium-235	7.1×10^8 years

Absorption of radiation

When considering the radiological effects of radiation, we must take into account not only the total energy absorbed but the mass of the material within which it is absorbed, e.g. for a dental X-ray, the absorbing mass would be the mass of tooth, gum, jaw and cheek.

Absorbed dose, *D*, is the energy *E* absorbed by unit mass.

Absorbed dose is measured in grays. 1 gray (Gy) = 1 joule per kilogram.

$$\boxed{D = \frac{E}{m}}$$

The absorption of energy by a substance depends on:

- the nature and thickness of the substance
- the type of radiation
- the energy of the particles or photons of the radiation.

Alpha radiation is absorbed within a fraction of a mm of tissue, which gives a very high absorbed dose because of the small absorbing mass.

Risk of biological harm

The risk of biological harm from an exposure to radiation depends on:

- the absorbed dose
- the kind of radiation, e.g. α, β, γ, or slow neutrons
- the body organs or tissues exposed.

Damage to living tissue can be caused by ionisation or excitation of the atoms or molecules in the tissue. These processes absorb the energy of the radiation, which eventually produces heat, chemical change or physical change.

To take account of the biological effects of the different kinds of radiations, a quality factor is defined.

The **quality factor**, *Q*, is a number that measures the **biological** effect of a radiation on living tissue.

Kind of radiation	**q (no units)**
x and γ rays	1
β particles	1
α particles	20
Neutrons: slow (thermal) fast	 2.3 10

Dose equivalent, H, is given by $\boxed{H = D \times Q}$

where H is measured in sieverts (Sv).

The **effective dose equivalent** takes into account the relative risks arising from exposure of different organs of the body. It is the effective dose equivalent that is used to indicate the risk to health from exposure to ionising radiations.

Dose equivalent rate $\dot{H}$ ***(H dot)***

This is given by the equation $\boxed{\dot{H} = \frac{H}{t}}$

The units of dose equivalent rate can be: mSv h^{-1}, mSv yr^{-1}, etc.

Example

In a year a worker receives the following exposures to radiation:
30 mGy of γ radiation and 400 μ Gy of fast neutrons.

What is his dose equivalent rate for the year?

$H = D \times Q$

Gamma	$H = 30 \times 10^{-3} \times 1$	=	30×10^{-3} Sv
Fast neutrons	$H = 400 \times 10^{-6} \times 10$	=	4×10^{-3} Sv

Total dose equivalent = 34 mSv and dose equivalent rate = 34 mSv yr^{-1}.

Background radiation

Man has always been exposed to a continual ‘background’ of radiation.

The average annual effective dose equivalent is approximately **2.0 mSv**, although this can vary from place to place.

Main contributing factors	Annual dose equivalent
Cosmic radiation	0.3 mSv
Radioactivity from rocks, soil, buildings	0.3 mSv
Radioactivity in human body	0.4 mSv
Inhaled Radon and daughter products	1.0 mSv

Primary cosmic rays (mostly protons) lose energy, by collisions in the atmosphere, and produce **secondary cosmic rays**, of γ-rays, electrons and neutrons that may reach the Earth’s surface.

Cosmic rays are more intense at high altitudes.

Rocks and soil contain traces of radioactive materials, mainly uranium-238, thorium-232 and their daughter products radium, and potassium-40. Granite is more radioactive than brick or sandstone. Areas where there are large amounts of granite have higher background rates, e.g. Aberdeen and Dartmoor.

Annual effective dose equivalent limits

For the public, exposure should not exceed **5 mSv** in any year and should not exceed 1 mSv per year on a long term basis.

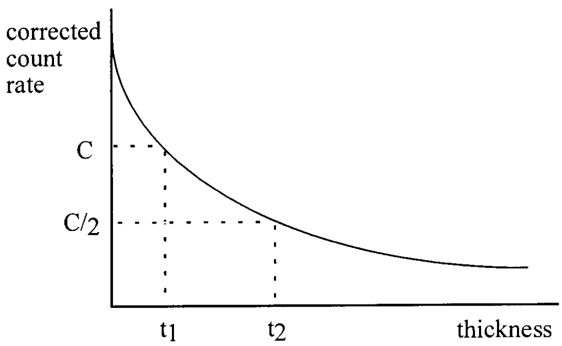
Radiation workers are permitted higher doses, because:
- they are unlikely to be either old and infirm or young and vulnerable
- they will be subject to regular medical examination
- they will have their exposure monitored.

Absorption of radiation by matter

Radiation levels can be reduced by placing absorbers of high atomic number, such as lead, in the path of the radiation.

Half-value thickness

The **half-life thickness** of an absorber is that thickness which, when placed in the path of the radiation, will reduce the count rate to one half of its previous value. It can be found from a graph of corrected count rate against thickness.



half-value thickness = $t_2 - t_1$

If the process is repeated for several different initial count rates, then an average value can be obtained.

Example

The dose equivalent rate due to gamma radiation from a spent fuel element is 10 Sv h^{-1}. The element is placed behind 60 mm of lead. If the half-value thickness for lead is 15 mm, calculate the dose equivalent rate behind the lead.

Number of half-value thicknesses = $\frac{60}{15} = 4$

Initial rate therefore halves itself four times.

$$\underset{1}{10 \rightarrow} \; \underset{2}{5 \rightarrow} \; \underset{3}{2.5 \rightarrow} \; \underset{4}{1.25 \rightarrow} \; 0.625$$ *(i.e. rate is 0.63 Svh^{-1})*

Safety

Reducing the dose equivalent rate

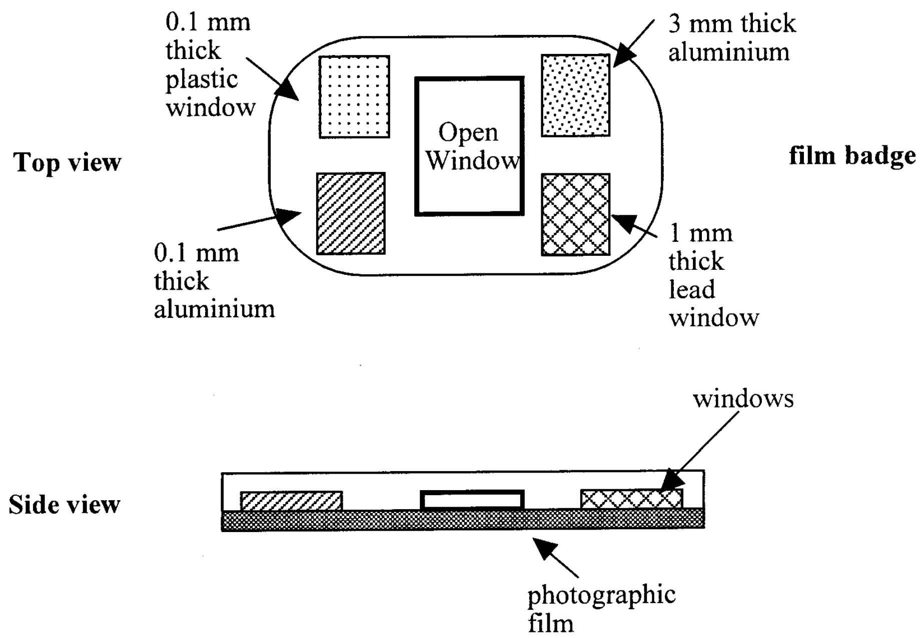
The absorption of radiation by matter provides the basis for the simplest method of reducing dose rates, i.e. shielding.

The other method of reducing exposure is by **increasing the distance** from a source. Radiation intensity decreases with increasing distance in the same way as light intensity, i.e. it also follows an **inverse square law**.

The **time** spent near a radioactive source should be kept to a minimum.

Monitoring exposure to radiation

The monitoring of the exposure of personnel to radiation is frequently carried out using film badges. These depend on the absorption of radiation by different materials and a diagram is shown below. By examining the area of film that has become fogged, it is possible to determine both the exposure, and the type of radiation.



RADIATION AND MATTER PROBLEMS

Waves

1. In an experiment to measure the period of a simple pendulum, the time for 20 complete swings was found to be 40 s.
   a) Why were 20 swings timed?
   b) What is the period of this pendulum?
   c) What is the frequency of this pendulum?
   d) A pupil counted 100 heartbeats during 60 swings of this pendulum. What is the period of his pulse?

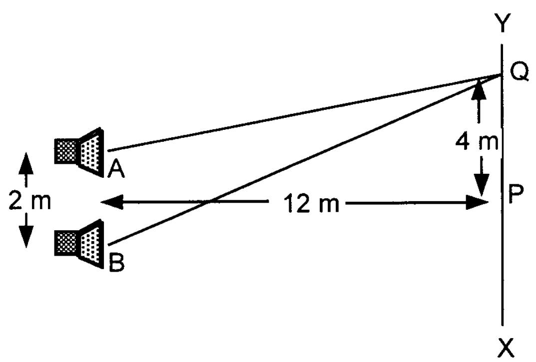
2. The 'mains' frequency is 50 Hz. How long does it take for one wave to be produced?

3. A 'long wave' radio station broadcasts on a frequency of 252 kHz.
   a) What is the period of these waves?
   b) What is the wavelength of these waves?

4. A green light has wavelength 546 nm.
   a) Express this wavelength in micrometres (μm).
   b) Express this wavelength in metres (using scientific notation).
   c) Calculate the frequency and period of these light waves.

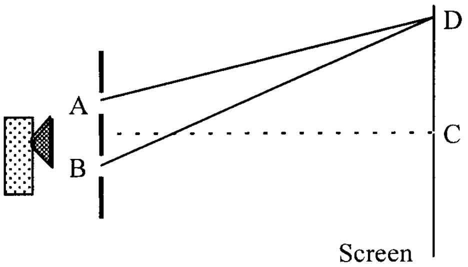
5. Explain how it is possible for interference to occur in the following situations:
   a) a single loudspeaker emitting sound in a room with no other objects in the room
   b) radio reception in a car when passing large buildings.

6. In an experiment on sound interference, two sources **A** and **B** are placed 2 m apart. As a girl walks from **X** to **Y** she hears a point of maximum loudness at point **P** and the next at point **Q**. Using information from the diagram below:
   a) find distances **AQ** and **BQ**
   b) calculate the wavelength of the sound
   c) calculate the frequency of the sound
   (speed of sound = 330 ms^{-1}).



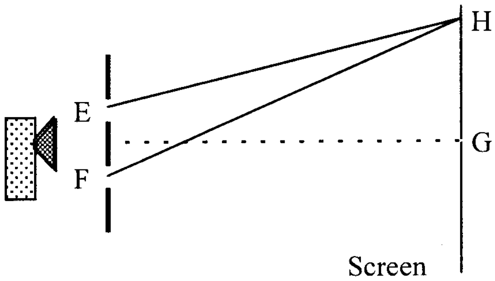
7. In the microwave experiment shown below, **C** is the zero order maximum and **D** is the first order maximum.
   AD = 52 cm and **BD** = 55 cm.

   a) What is the path difference at point **D**?
   b) What is the wavelength of the microwaves?
   c) What is the path difference to the second order maximum?
   d) What is the path difference to the minimum next to C?
   e) What is the path difference to the second order minimum?
   f) What is the path difference at point **C**?



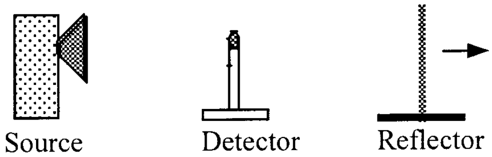
8. In a microwave interference experiment, **H** is the first **order** minimum, that is there is one other minimum between **H** and **G**. Measurement of distances **EH** and **FH** gives: **EH** = 42.1 cm and **FH** = 46.6 cm.

   Calculate the wavelength and frequency of the microwaves used.



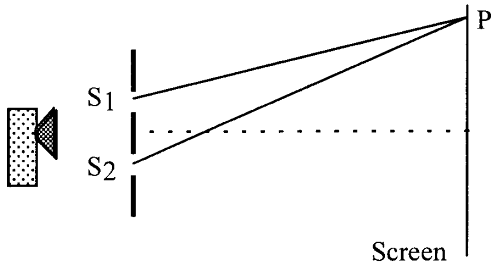
9. In a microwave experiment the waves reflected from a metal plate interfere with the incident waves on the detector. As the reflector is moved away from the detector, a series of maxima and minima are found.

   A maximum is found when the reflector is at a distance of 25 cm from the detector and a further 8 maxima are found as the reflector is moved to a distance of 37.8 cm from the detector.



   a) What is the average distance between maxima?
   b) Calculate the wavelength of the microwaves.
   c) Calculate the frequency of the microwaves.

10. In a microwave interference experiment, **P** is the **first** order minimum away from the centre. The measured distances and their uncertainties are:
$S_1P = 42.1 \pm 0.5$ cm $S_2P = 46.6 \pm 0.5$ cm



Calculate the wavelength of the microwaves and the uncertainty in this value of wavelength.

11. A grating with 600 lines per mm is used with a monochromatic source and gives the first order maximum at an angle of 20.5°.

    a) Calculate the wavelength of the source.
    b) What is the angle to the first order maximum if a grating of 1200 lines per mm was used?

12. Light of wavelength 600 nm is passed through a grating with 400000 lines per metre. Calculate the angle between the zero and first order maxima.

13. Light of wavelength 6.50×10^{-7} m is passed through a grating and the angle between the zero and third order maxima is 31.5°. Calculate the slit spacing of the grating.

14. Light of wavelength 500 nm is used with a grating of 500 lines/mm. Calculate the angle between the first and second order maxima.

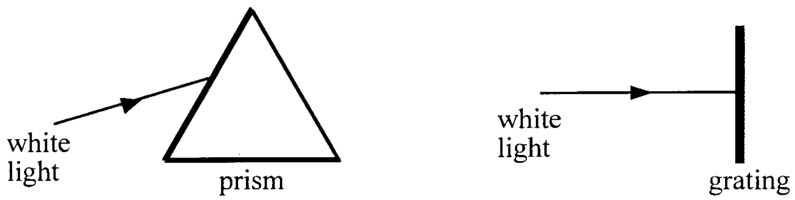
15. White light, with a range of wavelengths from 440 nm to 730 nm is passed through a grating with 500 lines/mm.

    a) Describe what would be seen.
    b) Explain the pattern produced.
    c) Calculate the angle between the extremes of the first order maximum, i.e. the angle between violet and red.

16. A green filter is placed in front of a white light source and the filtered light is passed through a grating with 300 lines/mm. A pattern of bright and dark bands is produced on a screen.

    a) What colour are the bright bands of light?
    b) Explain whether the spacing of the bright bands would increase or decrease when the following changes were made:
        i) using a blue filter instead of a green filter
        ii) using a grating with 600 lines/mm
        iii) using a brighter lamp
        iv) bringing the screen closer to the grating.

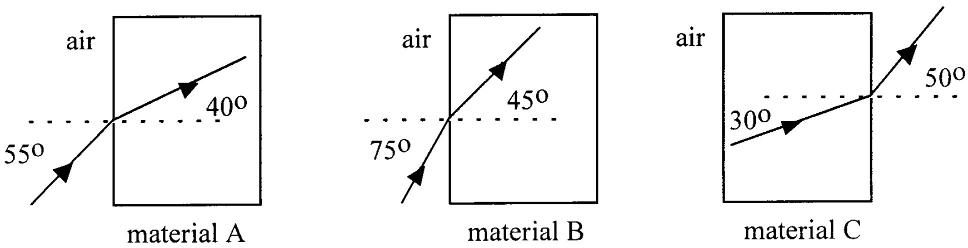
17. Spectra can be produced from white light by two methods as shown below.



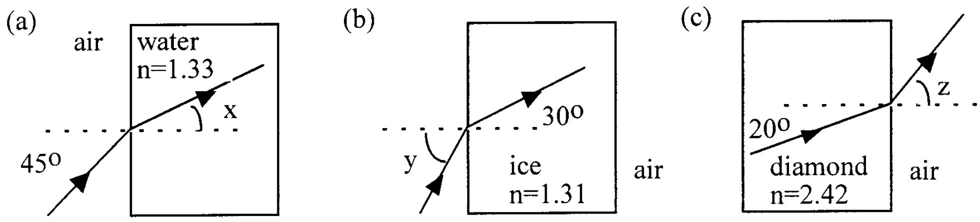
a) Copy and complete the above diagrams to show the spectra produced.
b) List the differences between the two spectra produced.

Refraction of light

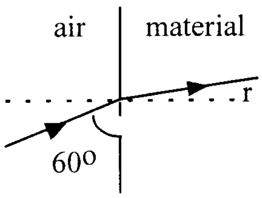
18. Calculate the refractive index *n* of each of the materials below:



19. Calculate the missing angle in each of the following diagrams:

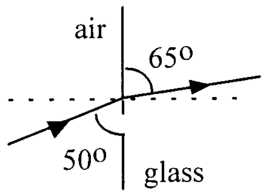


20. The refractive index of the material shown in the diagram below is 1.35.



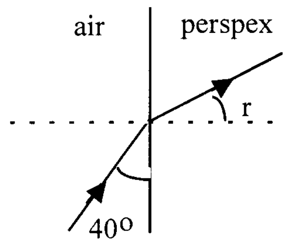
a) Calculate the angle *r*.
b) Find the velocity of the light in the material.

21. A ray of light of wavelength 6.00×10^{-7} m passes from air to glass as shown below.



a) Calculate the refractive index of the glass.
b) Calculate the speed of light in the glass.
c) Calculate the wavelength of the light in the glass.
d) Calculate the frequency of the light in air.
e) State the frequency of the light in the glass.

22. A ray of light of wavelength 500 nm passes from air into perspex of refractive index 1.50 as shown.

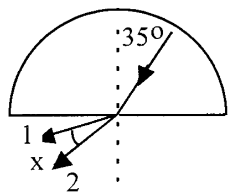


a) Calculate the angle *r*.
b) Calculate the speed of light in the perspex.
c) Calculate the wavelength of light in perspex.

23. The refractive index for red light in crown glass is 1.513 and for violet light it is 1.532.

a) Using this information, explain why white light can produce a spectrum when passed through crown glass.

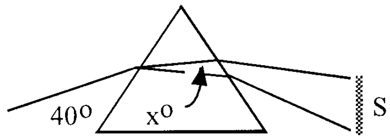
A ray of white light passes through a semi-circular block of crown glass as shown and produces a spectrum.



b) Which exit ray is red and which ray is violet?
c) Calculate the refracted angle in air for each of the exit rays.
d) Find angle *x*, the angle between the red and violet rays.

24. A ray of white light is dispersed by a prism producing a spectrum, S.
The angle $x°$ is found to be 0.7°.

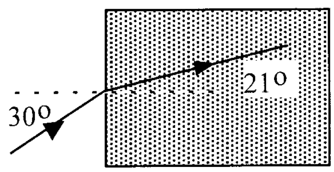
If the refractive index for red light is 1.51, calculate the refractive index for blue light.



25. Calculate the critical angle for each material using the refractive index given in the table below.

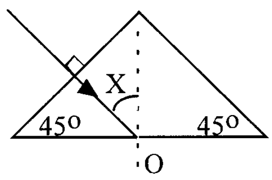
Material	***n***
Glass	1.54
Ice	1.31
Perspex	1.50

26. A beam of infrared radiation is refracted by a type of glass as shown.



a) Calculate the refractive index of the glass for infra red.
b) Calculate the critical angle of the glass for infra red.

27. A ray of light enters a glass prism of absolute refractive index 1.52, as shown:



a) Why does the ray not bend on entering the glass prism?
b) What is the value of angle **X**?
c) Why does the ray undergo total internal reflection at **O**?
d) Redraw the complete diagram showing the angles at **O** with their values.
e) Explain what would happen if the experiment was repeated with a prism of material with refractive index of 1.30.

28. The absolute refractive indices of water and diamond are 1.33 and 2.42 respectively.

 a) Calculate the critical angles for light travelling from each substance to air.
 b) Comment on the effect of the small critical angle of diamond on the beauty of a well cut stone.

Optoelectronics and semiconductors

29. A satellite is orbiting the Earth where the intensity of the Sun's radiation is 1.4 kW m^{-2}. Calculate the power received by the satellite's solar panels if they have an area of 15 m^2.

30. A pupil measures the light intensity of a 100 W light bulb as 02 W m^{-2} at a distance of 2 m. Calculate the intensity that would be measured at a distance of:
 a) 1 m from the light bulb
 b) 4 m from the light bulb.

31. In an experiment on light intensity, the following results were obtained:

Distance from point source *d* (m)	1.0	1.4	2.2	2.8	3.0
Measured intensity *I* (W m^{-2})	85	43	17.6	10.8	9.4

 a) Sketch the apparatus that could be used to obtain these results.
 b) Use an appropriate format to show the relationship between the intensity *I* and the distance *d*.
 c) Calculate the intensity at a distance of 5 m from the source.
 d) At what distance would the intensity of the light be 150 W m^{-2}?

32. At a certain point on the Earth's surface, the Sun's radiation has an intensity of 200 W m^{-2}.

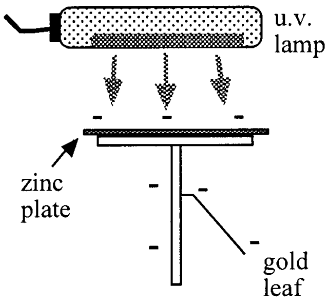
 a) What area of solar cells would be required to produce a power output of 1 mW?
 b) If the cells were only 15% efficient, what additional area of solar cells would be required?

33. In an experiment to measure the intensity of a light source, the power of the source is measured as 150 ± 1 W and the area of the surface as 1.8 ± 0.1 m^2.

 Calculate the intensity and the uncertainty in the intensity. Express your answer in the form: value ± uncertainty.

34. Radiation of frequency 5.0×10^{14} Hz can eject electrons from a metal surface.

a) Explain why the leaf rises when the electroscope is initially charged.

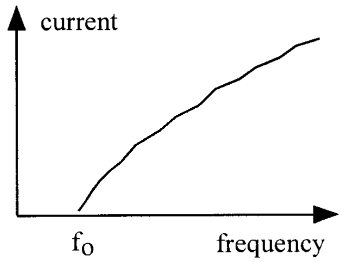


An ultraviolet lamp of frequency 5.4×10^{14} Hz then shines onto the cap of the electroscope.

b) Describe and explain what happens to the gold leaf.

c) Explain the effect each of the following changes has on the gold leaf of the negatively charged electroscope:
   i) using a more intense ultraviolet lamp
   ii) moving the ultra violet lamp further away from the cap
   iii) shining red light onto the electroscope cap instead of u.v. radiation
   iv) using a tin plate instead of the zinc plate and illuminated with u.v. radiation
   v) charging the electroscope positively instead of negatively.

35. In a study of photoelectric currents, the graph shown was obtained.



a) What name is given to the frequency f_o?
b) Explain why no current is detected if the frequency of the incident radiation is below f_o.

36. For a certain metal, the energy required to eject an electron from the atom is 3.3×10^{-19} J.

a) Calculate the minimum frequency of radiation required to emit a photoelectron from the metal.
b) Explain whether or not photoemission would take place using radiation of:
   i) frequency 4×10^{14} Hz
   ii) wavelength 5×10^{-7} m.

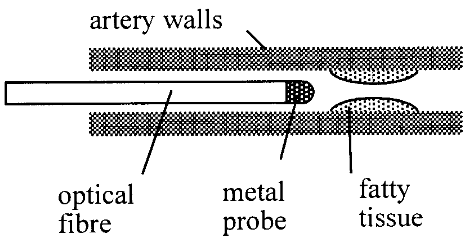
37. The minimum energy required to remove an electron from zinc is 6.1×10^{-19} J.

a) What name is given to this minimum energy?
b) Calculate the value of fo for zinc.
c) Photons with a frequency of 1.2×10^{15} Hz strike a zinc plate ejecting an electron from the surface.
   i) How much extra energy will the electron have after it is released?
   ii) What will be the form of this extra energy?

38. Radiation of frequency 5.0×10^{14} can eject electrons from a metal surface.

a) Calculate the energy of each photon of radiation.
b) If the electrons are ejected from the surface with kinetic energy of 7.0×10^{-20} J, calculate the work function of the metal.

39. 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.



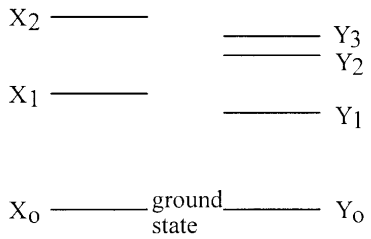
The laser has a power of 8 W and uses a wavelength of 490 nm.

a) How much energy is delivered in 5 s?
b) Calculate the number of photons of radiation required to provide this 5 s pulse of energy from the 8 W laser.

40. When the light emitted by a particular material is observed through a spectroscope, it appears as four distinct lines.

a) What name is given to this kind of emission spectrum?
b) Explain why a series of specific, coloured lines is observed.
c) The red line in the spectrum coincides with a wavelength of 680 nm. Calculate the energy of the photons of light that produced this line.
d) What difference would be observed if the spectroscope was used to examine the light emitted from a torch bulb (filament lamp)?

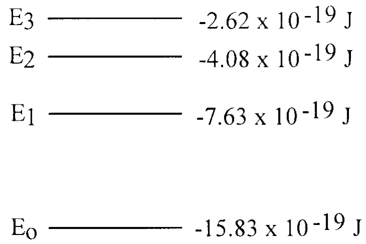
41. Shown in the diagram below are the energy levels for two atoms **X** and **Y**, drawn to the same scale.



a) i) How many downward transitions are possible between the energy levels of each atom?
   ii) How many lines could appear in the emission spectrum of each element?
   iii) Sketch the energy levels for each atom, showing the possible transitions.

b) Which transition in these diagrams will give rise to the emitted radiation of:
   ii) lowest frequency?
   iii) shortest wavelength?

42. Shown below is the energy level diagram of a particular element.



a) How many lines could appear in the emission spectrum of this element?
b) Calculate the frequencies of the photons arising from:
   ii) the largest energy transition
   iii) the smallest energy transition.
c) Show whether any of the emission lines in the spectrum correspond to frequencies within the visible spectrum.
d) Explain which transition would produce the photons most likely to cause photoemission in a metal.

43. From your notes, sketch and label the energy level diagram for the hydrogen atom from energy levels E_0 to E_3.

a) How many emission lines are possible from electron transitions between these energy levels?
b) Which of the following radiations could be absorbed by the electrons in a hydrogen atom?
   ii) frequency 2.92×10^{15} Hz
   iii) frequency 1.57×10^{15} Hz
   iv) wavelength 4.89×10^{-7} m.

44. Explain why the absorption spectrum of an atom has dark lines corresponding to frequencies present in the emission spectrum of the atom.

45. a) Explain the presence of the Fraunhofer Lines, the dark lines that appear in the spectrum of sunlight.

    b) How are they used to determine the gases that are present in the solar atmosphere?

46. Explain the difference between spontaneous emission and stimulated emission of radiation.

47. a) In stimulated emission, how does the energy and phase of the emitted photon compare to that of the stimulating photon?

    b) The stimulated and stimulating photons are said to be coherent. Explain what is meant by the term 'coherent'.

48. Many materials can be used to make lasers. For example, ruby, neon and argon. What is significant about the probability of spontaneous emission in materials used to make lasers?

49. State three differences between laser light and light from a filament lamp.

50. A laser has mirrors at either end of the tube.
    a) Explain why the mirrors must be perfectly parallel.
    b) Explain the function of the partially-silvered mirror at one end of the laser.

51. A laser beam of power 0.1 mW would be harmful if it entered the eye but light from a 150 W filament lamp is perfectly safe. At a distance of 2 m, the laser beam has a diameter of 1 mm.

    By calculating the intensity of the laser and lamp at a distance of 2 m, show why the laser is harmful to the eye but the mains lamp is not.

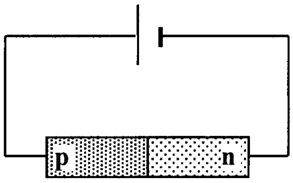
52. To increase the conductivity of a semiconductor material, the material can be doped.
    a) Explain, giving an example, what is meant by 'doping' a semiconductor.
    b) Why does doping decrease the resistance of a semiconductor.

53. a) If germanium (4 electrons in the outer shell) is doped with phosphorus (5 electrons in the outer shell), what kind of semi-conductor is formed?

    b) How can a doped semiconductor of either type still have a neutral overall charge?

54. Describe the movement of the majority charge carriers when a current flows through:
    a) an n-type semiconductor material
    b) a p-type semiconductor material.

55. A p-n junction diode is connected across a d.c. supply as shown.



a) Is the diode connected in forward or reverse bias?
b) Describe the movement of both majority charge carriers across the p-n junction?
c) What kind of charge is the only one that actually moves across the junction?

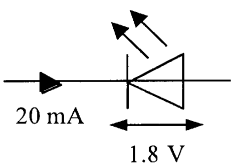
56. Both ordinary diodes and LEDs emit quanta of radiation from the junction as positive and negative charge carriers recombine.
a) Does the junction have to be forward-biased or reverse-biased for this to happen?
b) What form does this emitted energy take when emitted by:
ii) an LED
iii) an ordinary junction diode?

57. A particular LED is measured as having a recombination energy of 3.12×10^{-19} J.
a) What colour of light is emitted by this LED?
b) What factor about the construction of the LED determines the colour of the emitted light?

58. a) State two advantages of an LED over an ordinary filament lamp.

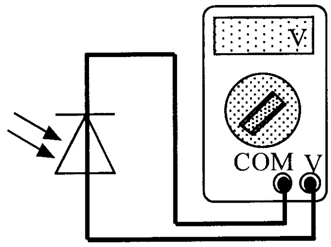
b) An LED is rated as follows:
operating p.d. 1.8 V, forward current 20 mA.

This LED is to be operated from a 6 V d.c. power supply.



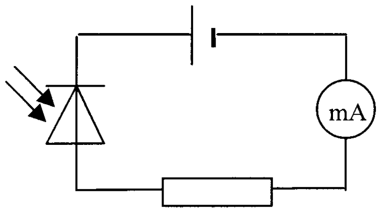
i) Sketch the circuit diagram to allow this to be possible, including a protective resistor.
ii) Calculate the value of the protective resistor to allow the LED to operate normally.

59. The diagram below shows a photodiode connected to a voltmeter.



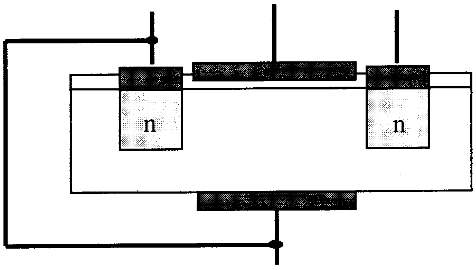
a) State the mode that the photodiode is operating in.
b) Explain how an e.m.f. is created across the junction when light is incident on it.
c) Explain why increasing the light intensity incident on the photodiode increases the e.m.f. produced.

60. A photodiode is connected in reverse bias in a series circuit as shown.



a) What name is given to this mode of operation of the photodiode?
b) Why is the photodiode connected in reverse bias?
c) What value of current is measured in the circuit when the photodiode is in darkness? Explain your answer.
d) What happens to the current in the circuit as the light intensity increases on the photodiode?
e) What happens to the effective 'resistance' of the photodiode as the light intensity increases? Explain why this happens.
f) What electrical device is the photodiode behaving similarly to?

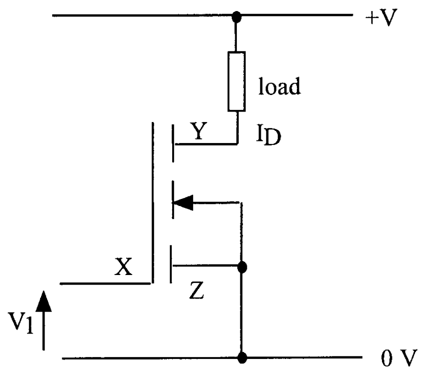
61. The diagram below shows some constructional details of an n-channel enhancement MOSFET.



Copy the diagram and add labels to show the:
gate, source, drain, substrate, channel, implant, oxide layer.

62. a) Draw the circuit symbol for an n-channel MOSFET. Mark on the symbol the gate, drain and source.
    b) Describe the operation of the n-channel MOSFET indicating the parts played by the gate, source and drain.

63. The diagram below shows a resistive load being switched on by a transistor.
    a) Name the transistor being used.
    b) Name the terminals **X**, **Y** and **Z**.
    c) Name the current I_D.
    d) Describe how the load is switched on and off.



Nuclear reactions

64. Give reasons why the alpha particles in the Rutherford Scattering Experiment are scattered by the thin gold foil.

65. Describe the Rutherford model of the atom.

66. Here is a list of atomic numbers:
    a) 6 b) 25 c) 47 d) 80 e) 86 f) 92.

    Use a periodic table to identify the corresponding elements.

67. For each of the isotopes below state:
    a) the number of protons
    b) the number of neutrons.

i) $^{7}_{3}Li$	ii) $^{64}_{30}Zn$	iii) $^{109}_{47}Ag$
iv) $^{131}_{54}Xe$	v) $^{239}_{94}Pu$	vi) $^{257}_{103}Lw$

68. Neon has two main isotopes, $^{20}_{10}Ne$ and $^{22}_{10}Ne$, and has a relative atomic mass of 20.2.

    What does this indicate about the relative abundance of each isotope?

69. Find the following missing particles or nuclides:

$$^{228}_{90}\text{Th} \rightarrow\ ^{224}_{88}\text{Ra} + \text{A} \qquad\qquad ^{220}_{86}\text{Rn} \rightarrow\ ^{4}_{2}\text{He} + \text{B}$$

$$^{211}_{82}\text{Pb} \rightarrow\ ^{211}_{83}\text{Bi} + \text{C} \qquad\qquad \text{D} \rightarrow\ ^{219}_{86}\text{Rn} \rightarrow\ ^{4}_{2}\text{He}$$

70. Part of a radioactive decay series is shown below:

$$^{235}_{92}\text{U} \rightarrow\ ^{231}_{90}\text{Th} \rightarrow\ ^{231}_{91}\text{Pa} \rightarrow\ ^{227}_{89}\text{Ac}$$

a) Identify the particle emitted at each stage.
b) Such a series does not always give a complete picture of the radiations emitted by each nucleus. Give an explanation.

71. For a particular radionuclide sample 8×10^7 disintegrations take place in 40 s. Calculate the activity of the source.

72. A particular radionuclide has a half life of 8 hours. What fraction of the nuclei will remain after one day?

73. A half-life experiment provided the following readings:

Time (s)	**Count rate (counts per second)**
0	56
30	41
60	29
90	23
120	17
150	13
180	10
210	7
240	6

a) What is the background count rate?
b) Use an appropriate format to determine the half life of the source.

74. How much energy is released when the following decrease in mass, measured in various fission reactions, is transformed into energy?

a) 3.25×10^{-28} kg b) 2.01×10^{-28} kg

c) 1.62×10^{-28} kg d) 2.85×10^{-28} kg

75. The following equation represents a nuclear reaction involving the release of energy.

$$^{3}_{1}H + {}^{2}_{1}H \rightarrow {}^{4}_{2}He + {}^{1}_{0}n$$

The masses of these particles are given below.

Mass of $^{1}_{1}H = 1.672 \times 10^{-27}$ kg

Mass of $^{2}_{1}H = 3.342 \times 10^{-27}$ kg

Mass of $^{3}_{1}H = 5.005 \times 10^{-27}$ kg

Mass of $^{4}_{2}He = 6.647 \times 10^{-27}$ kg

Mass of $^{1}_{0}n = 1.675 \times 10^{-27}$ kg

a) Calculate the decrease in mass that occurs when this reaction takes place.
b) Find the energy released in this reaction.
c) What is the name given to this type of nuclear reaction?

76. Plutonium can undergo the following nuclear reaction:

$$^{239}_{94}Pu + {}^{1}_{0}n = Te + {}^{100}_{42}Mo + 3\ {}^{1}_{0}n$$

a) State the mass number and atomic number of Te.
b) The masses of the nuclei involved are given below.

Particle	n	Pu	Te	Mo
Mass/kg	1.675×10^{-27}	396.741×10^{-27}	227.420×10^{-27}	165.809×10^{-27}

Calculate the decrease in mass that occurs.

c) Find the energy released in this reaction.

Dosimetry and safety

77. For an absorbed dose of 50 mGy, calculate the dose equivalent for the following radiations:
    a) X-rays
    b) protons
    c) slow neutrons.

78. A worker receives the following absorbed doses:
    - γ–radiation 150 μGy
    - Thermal neutrons 240 μGy
    - Fast neutrons 90 μGy.

    a) What is the dose equivalent for each radiation?
    b) Find the total dose equivalent.
    c) If the doses were received in 6 hours, calculate the dose equivalent rate in μSv h^{-1}.

79. It is found that a radiation worker has received a dose equivalent of 500 μSv in the course of a 25-hour working week. Calculate the dose equivalent rate in μSv h^{-1}.

80. The cosmic ray detector on board an aircraft indicates a dose equivalent rate of 15 μSv h^{-1}.
    a) Calculate the dose equivalent to those on board during a 4-hour flight.
    b) How many such flights would a crew member have to make in a year to receive the maximum permissible dose equivalent of 5 mSv in a year?

81. State three sources of background radiation.

82. Give the annual effective dose equivalent limits for:
    a) the general public
    b) radiation workers.

83. A pupil investigating the absorption of γ-rays by lead obtains the following results:

Thickness of lead (mm)	**Corrected count rate (counts per second)**
0	45
4	37
7	31
11	25
22	15
36	7

Use an appropriate format to find the half-value thickness of lead for γ-rays.

84. The activity of a γ source is 256 counts per minute. When 30 cm of absorbing material is placed between the source and detector, the count rate is reduced to 64 counts per minute. Calculate the half-value thickness of the absorber.

85. A certain material has a half-value thickness of 50 mm. A source has a dose equivalent rate of 24 $\mu Sv\ h^{-1}$. Some of the material is placed between the source and detector and the dose equivalent rate is reduced to 3 $\mu Sv\ h^{-1}$. Calculate the thickness of the material.

86. The half-value thickness of water is 200 mm. A used fuel element gives a dose equivalent rate of 10 $Sv\ h^{-1}$. Calculate the dose equivalent rate when 1 m of water is placed between source and detector.

87. A ^{60}Co source has, at distance of 100 mm, a dose equivalent rate of 8 $mSv\ h^{-1}$.

    What thickness of lead will reduce the dose equivalent rate at this distance to 1 $mSv\ h^{-1}$?

    (The half-value thickness of lead for these γ-rays is 11 mm.)