12 Quantum and nuclear physics

ESSENTIAL IDEAS

- The microscopic quantum world offers a range of phenomena, the interpretation and explanation of which require new ideas and concepts not found in the classical world.
- The idea of discreteness that we met in the atomic world continues to exist in the nuclear world as well.

12.1 The interaction of matter with radiation – *the microscopic quantum world offers a range of phenomena, the interpretation and explanation of which require new ideas and concepts not found in the classical world*

In 1900 it was believed that physics was almost fully understood, although there were a few knowledge 'gaps', such as the nature of atoms and molecules, and the ways in which radiation interacted with matter. Many physicists believed that filling in these gaps was unlikely to involve any new theories. However, within a few years the 'small gaps' were seen to be fundamental and radically new theories were required. One important discovery was that energy only comes in certain *discrete* (separate) amounts known as quanta (singular: quantum). The implications of this discovery were enormous and collectively they are known as *quantum physics*.

As quantum physics developed, some classical concepts had to be abandoned. There was no longer a clear distinction between particles and waves. The most fundamental change was the discovery that systems change in ways that cannot be predicted precisely; only the probability of events can be predicted.

Photons

The German physicist Max Planck was the first to propose (in 1900) that the energy transferred by electromagnetic radiation was in the form of a very large number of separate, individual amounts of energy (rather than continuous waves). These discrete 'packets' of energy are called *quanta*. Quanta are also commonly called **photons**. The concept of photons was introduced in Chapter 7 as a way of explaining why atoms emit or absorb radiation in quantized amounts, and why this produces characteristic line spectra.

This very important theory, developed further by Albert Einstein in the following years, essentially describes the nature of electromagnetic radiation as being *particles*, rather than *waves*. ('Wave–particle duality' is discussed on page 516.)

The energy, E, carried by each photon (quantum) depends on its frequency, f, and is given by the relationship:

$$E = hf$$

h is Planck's constant. Its value (6.63×10^{-34} J s) and the equation are given in the *Physics data booklet*.

The following questions revise these ideas. We will then consider the experimental evidence that supports the photon model of electromagnetic radiation (the photoelectric effect).

1 Calculate the number of photons emitted every second from a mobile phone operating at a frequency of 850 MHz and at a radiated power of 780 mW.

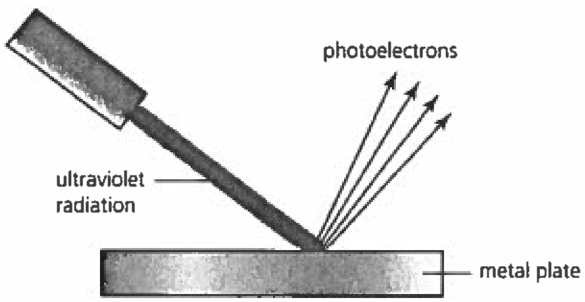
2 What is the approximate ratio of the energy of a photon of blue light to the energy of a photon of red light?

3 A detector of very low intensity light receives a total of 3.32×10^{-17} J from light of wavelength 600 nm. Calculate the number of photons received by the detector.

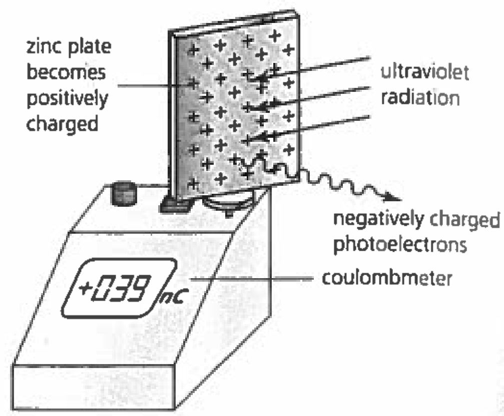
4 a Calculate an approximate value for the energy of an X-ray photon in joules and in electronvolts.
b Suggest a reason why exposure to X-rays of low intensity for a short time is dangerous, but relatively high continuous intensities of visible light causes us no harm.

■ The photoelectric effect

When electromagnetic radiation is directed on to a clean surface of some metals, electrons may be ejected. This is called the photoelectric effect (Figure 12.1) and the ejected electrons are known as photoelectrons. Under suitable circumstances the photoelectric effect can occur with visible light, X-rays and gamma rays, but it is most often demonstrated with ultraviolet radiation and zinc. Figure 12.2 shows a typical arrangement.



■ **Figure 12.1 The photoelectric effect – a stream of photoelectrons is emitted from a metal surface illuminated with ultraviolet radiation**



■ **Figure 12.2** Demonstration of the photoelectric effect

Ultraviolet radiation is shone on to a zinc plate attached to a coulombmeter (which measures very small quantities of charge). The ultraviolet radiation causes the zinc plate to become positively charged because some negatively charged electrons on the (previously neutral) zinc plate have gained enough kinetic energy to escape from the surface.

Simple investigations of the photoelectric effect show a number of key features.

- If the intensity of the radiation is increased, the charge on the plate increases more quickly (because more photoelectrons are being released every second).
- There is no time delay between the radiation reaching the metal surface and the emission of photoelectrons. The release of photoelectrons from the surface is *instantaneous*.
- The photoelectric effect can only occur if the frequency of the radiation is above a certain *minimum* value. The lowest frequency for emission is called the threshold frequency, f_0. (Alternatively, we could say that there is *maximum* wavelength above which the effect will not occur.) If the frequency used is lower than the threshold frequency, the effect will not occur *even if the intensity of the radiation is greatly increased*. The threshold frequency of zinc, for example, is 1.04×10^{15} Hz, which is in the ultraviolet part of the spectrum. Visible light will not release photoelectrons from zinc (or most other common metals).
- For a given incident frequency the photoelectric effect occurs with some metals but not with others. This is because different metals have different threshold frequencies.

Explaining the photoelectric effect: the Einstein model

If we tried to use the wave theory of radiation to make predictions about the photoelectric effect, we would expect the following. (1) Radiation of *any* frequency will cause the photoelectric effect if the intensity is made high enough. (2) There may be a delay before the effect begins because it needs time for enough energy to be provided (like heating water until it boils).

These predictions are *wrong*, so an alternative theory is needed. Einstein realized that we cannot explain the photoelectric effect without first understanding the quantum nature of radiation.

The Einstein model explains the photoelectric effect using the concept of photons. When a photon in the incident radiation interacts with an electron in the metal surface, it transfers *all* of its energy to that electron. It should be stressed that a *single* photon can only interact with a *single* electron and that this transfer of energy is *instantaneous*; there is no need to wait for a build-up of energy. If a photoelectric effect is occurring, increasing the intensity of the radiation only increases the number of photoelectrons, not their energies.

Einstein realized that some of the energy carried by the photon (and then given to the electron) was used to overcome the attractive forces that normally keep an electron within the metal surface. The remaining energy is transferred to the kinetic energy of the newly released (photo) electron. Using the principle of conservation of energy, we can write:

$$\text{energy carried by photon} = \text{work done in removing the electron from the surface} + \text{kinetic energy of photoelectron}$$

But the energy required to remove different electrons is *not* always the same. It will vary with the position of the electron with respect to the surface. Electrons closer to the surface will require less energy to remove them. However, there is a well-defined *minimum* amount of energy needed to remove an electron, and this is called the **work function**, Φ, of the metal surface. Different metals have different values for their work functions. For example, the work function of a clean zinc surface is 4.3 eV. This means that *at least* 4.3 eV (= 6.9×10^{-19} J) of work has to be done to remove an electron from zinc.

To understand the photoelectric effect we need to compare the photon's energy, hf, to the work function, Φ, of the metal:

- $hf < \Phi$

  If an incident photon has less energy than the work function of the metal, the photoelectric effect cannot occur. Radiation that may cause the photoelectric effect with one metal may not have the same effect with another (which has a different work function).

- $hf\ (= hf_0) = \Phi$

  At the *threshold frequency*, f_0, the incident photon has exactly the same energy as the work function of the metal. We may assume that the photoelectric effect occurs but the released photoelectron will have zero kinetic energy.

- $hf > \Phi$

  If an incident photon has more energy than the work function of the metal, the photoelectric effect occurs and a photoelectron will be released. Photoelectrons produced by different photons (of the same frequency) will have a range of different kinetic energies because different amounts of work will have been done to release them.

It is important to consider the situation in which the *minimum* amount of work is done to remove an electron (equal to the work function):

energy carried by photon = work function + *maximum* kinetic energy of photoelectron

Or in symbols:

$$hf = \Phi + E_{max}$$

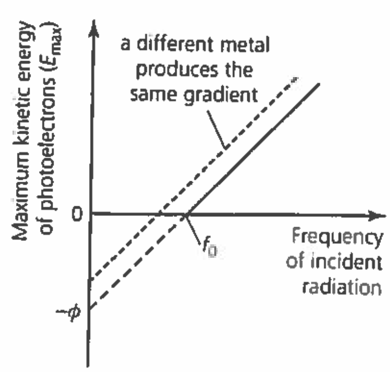
Or:

$$E_{max} = hf - \Phi$$

This equation is often called Einstein's photoelectric equation and it is given in the *Physics data booklet*. Because $hf_0 = \Phi$, we can also write this as:

$$hf = hf_0 + E_{max}$$

Figure 12.3 shows a graphical representation of how the maximum kinetic energy of the emitted photons varies with the frequency of the incident photons. The equation of the line is $E_{max} = hf - \Phi$, as above.



■ Figure 12.3 Theoretical variation of maximum kinetic energy of photoelectrons with incident frequency (for two different metals)

We can take the following measurements from this graph:

- The gradient of the line is equal to Planck's constant, h. (Compare the equation of the line to $y = mx + c$.) Clearly the gradient is the same for all circumstances because it does not depend on photon frequencies or the metal used.
- The intercept on the frequency axis gives us the value of the threshold frequency, f_0.
- A value for the work function can be determined from:
  i when $E_{max} = 0$, $\Phi = hf_0$; or
  ii when $f = 0$, $\Phi = -E_{max}$

Worked example

1 Radiation of wavelength 5.59×10^{-8} m was incident on a metal surface that had a work function of 2.71 eV.

a What was the frequency of the radiation?
b How much energy is carried by one photon of the radiation?
c What is the value of the work function expressed in joules?
d Did the photoelectric effect occur under these circumstances?
e What was the maximum kinetic energy of the photoelectrons?
f What is the threshold frequency for this metal?
g Sketch a fully labelled graph to show how the maximum kinetic energy of the photoelectrons would change if the frequency of the incident radiation was varied.

a $f = \frac{c}{\lambda} = \frac{3.00 \times 10^{8}}{5.59 \times 10^{-8}} = 5.37 \times 10^{15}$ Hz

b $E = hf$

$E = (6.63 \times 10^{-34}) \times (5.37 \times 10^{15})$

$E = 3.56 \times 10^{-18}$ J

c $2.71 \times (1.60 \times 10^{-19}) = 4.34 \times 10^{-19}$ J

d Yes, because the energy of each photon is greater than the work function.

e $E_{max} = hf - \Phi$

$E_{max} = (3.56 \times 10^{-18}) - (4.34 \times 10^{-19}) = 3.13 \times 10^{-18}$ J

f $\Phi = hf_0$ so $f_0 = \frac{\Phi}{h} = \frac{4.34 \times 10^{-19}}{6.63 \times 10^{-34}} = 6.54 \times 10^{-14}$ Hz

g The graph should be similar to Figure 12.3, with numerical values provided for the intercepts.

5 Repeat the worked example above but for radiation of wavelength 6.11×10^{-7} m incident on a metal with a work function of 2.21 eV. Omit e.

6 a Explain how Einstein used the concept of photons to explain the photoelectric effect.
b Explain why a wave model of electromagnetic radiation is unable to explain the photoelectric effect.

7 The threshold frequency of a metal is 7.0×10^{14} Hz. Calculate the maximum kinetic energy of the electrons emitted when the frequency of the radiation incident on the metal is 1.0×10^{15} Hz.

8 a The longest wavelength that emits photoelectrons from potassium is 550 nm. Calculate the work function (in joules).
b What is the threshold wavelength for potassium? What is the name for this kind of radiation?
c Name one colour of visible light that will *not* produce the photoelectric effect with potassium.

9 When electromagnetic radiation of frequency 2.90×10^{15} Hz is incident on a metal surface, the emitted photoelectrons have a maximum kinetic energy of 9.70×10^{-19} J. Calculate the threshold frequency of the metal.

Experiments to test the Einstein model

Investigating stopping potentials

To test Einstein's equation (model) for the photoelectric effect, it is necessary to measure the maximum kinetic energy of the photoelectrons emitted under a variety of different circumstances. In order to do this the kinetic energy must be transferred to another (measurable) form of energy.

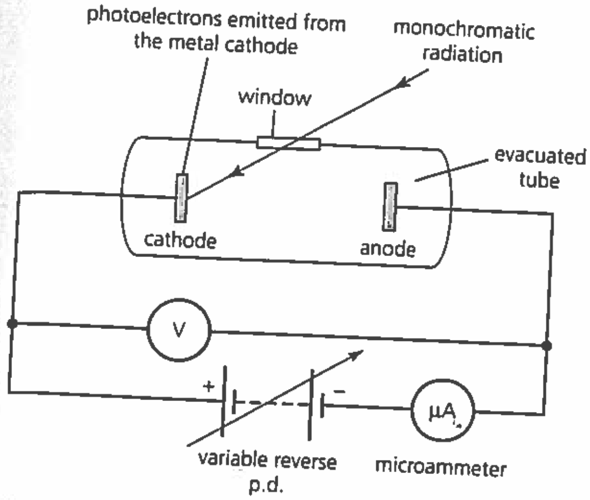


Figure 12.4 Experiment to test Einstein's model of photoelectricity

The kinetic energy of the photoelectrons can be transferred to electric potential energy if they are repelled by a negative voltage (potential). This experiment was first performed by the American physicist Robert Millikan and a simplified version is shown in Figure 12.4.

Ideally *monochromatic* radiation should used, but it is also possible to use a narrow range of frequencies such as those obtained by using coloured filters with white light.

When radiation is incident on a suitable emitting surface, photoelectrons will be released with a range of different energies, as explained previously. Because it is emitting negative charge, this surface can be described as a cathode (the direction of conventional current flow will be out of the cathode and around the circuit). Any photoelectrons that have enough kinetic energy will be able to move across the tube and reach the other electrode, the anode. The tube is *evacuated* (the air is removed to create a vacuum) so that the electrons do not collide with air molecules during their movement across the tube.

The most important thing to note about this circuit is that the (variable) source of p.d. is connected the 'wrong way around'. We say that it is supplying a reverse potential difference across the tube. This means that there is a negative voltage (potential) on the anode that will *repel* the photoelectrons. Photoelectrons moving towards the anode will have their kinetic energy reduced as it is transferred to electrical potential energy. (Measurements for positive potential differences can be made by reconnecting the battery the 'correct' way.)

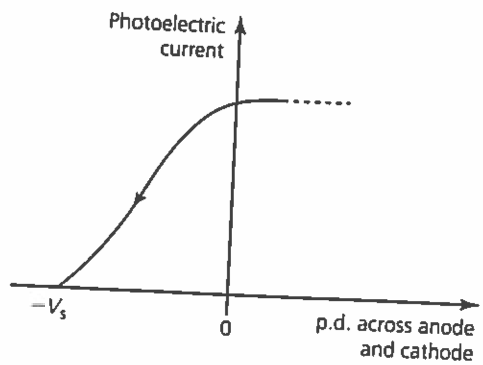


Figure 12.5 Increasing the reverse p.d. decreases the photoelectric current

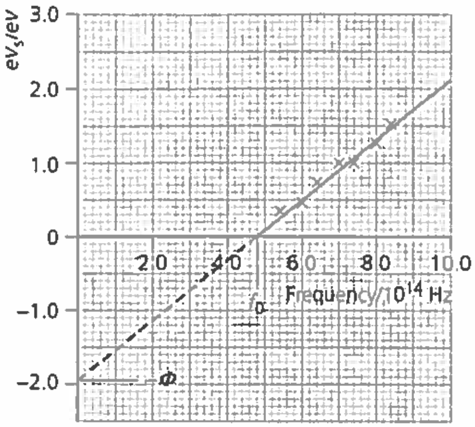
Any flow of charge across the tube and around the circuit can be measured by a sensitive ammeter (microammeter or picoammeter). When the reverse potential on the anode is increased from zero, more and more photoelectrons will be prevented from reaching the anode and this will decrease the current. (Remember that the photoelectrons have a range of different energies.) Eventually the potential will be big enough to stop even the most energetic of photoelectrons, and the current will fall to zero (Figure 12.5).

The potential on the anode needed to just stop all photoelectrons reaching it is called the stopping potential, V_s.

Because, by definition, potential difference = energy transferred/charge, after measuring V_s we can use the following equation to calculate values for the maximum kinetic energy of photoelectrons under a range of different circumstances:

$$E_{max} = eV_s$$

For convenience, it is common to quote all energies associated with the photoelectric effect in electronvolts (eV). In which case, the maximum kinetic energy of the photoelectrons is



■ **Figure 12.6 Experimental results showing variation of maximum potential energy (eV_s) of photoelectrons with incident frequency**

numerically equal to the stopping potential. That is, if the stopping potential is, say, 3 V, then E_{max} = 3 eV.

Einstein's equation ($E_{max} = hf - \Phi$) can be rewritten as:

$$eV_s = hf - \Phi$$

By *experimentally* determining the stopping potential for a range of different frequencies, the *theoretical* graph shown previously in Figure 12.3 can now be confirmed by plotting a graph from actual data, as shown in Figure 12.6.

- The threshold frequency, f_0, can be determined from the intercept on the frequency axis (4.8×10^{14} Hz).
- The work function, Φ, can be calculated from $\Phi = hf_0$, or from the intercept on the eV_s axis (1.9 eV).
- A value for Planck's constant, h, can be determined from the gradient (6.5×10^{-34} J s).

10 Use Figure 12.6 to confirm the values given above for f_0, Φ and h.

11 Calculate the maximum kinetic energy of photoelectrons emitted from a metal if the stopping potential was 2.4 eV. Give your answer in joules and in electronvolts.

12 Make a copy of Figure 12.5 and add lines to show the results that would be obtained with:
a the same radiation, but with a metal of higher work function
b the original metal and the same frequency of radiation, but using radiation with a greater intensity.

13 In an experiment using monochromatic radiation of frequency 7.93×10^{14} Hz with a metal that had a threshold frequency of 6.11×10^{14} Hz, it was found that the stopping potential was 0.775 V. Calculate a value for Planck's constant from these results.

Investigating photoelectric currents

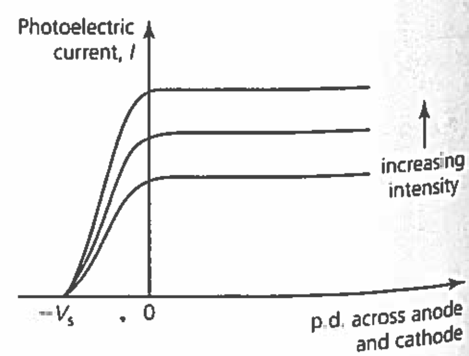
Using apparatus similar to that shown in Figure 12.4, it is also possible to investigate quantitatively the effects on the photoelectric current of changing the intensity, the frequency, and the metal used in the cathode.

- **Intensity** – Figure 12.7 shows the photoelectric currents produced by monochromatic radiation of the same frequency at three different intensities.

  For positive potentials, each of the photoelectric currents remain constant because the photoelectrons are reaching the anode at the same rate as they are being produced at the cathode, and this does not depend on the size of the positive potential on the anode.

  Greater intensities (of the same frequency) produce higher photoelectric currents because there are more photons releasing more photoelectrons (of the same range of energies).

  Because the maximum kinetic energy of photoelectrons depends only on frequency and not intensity, all these graphs have the same value for stopping potential, V_s.



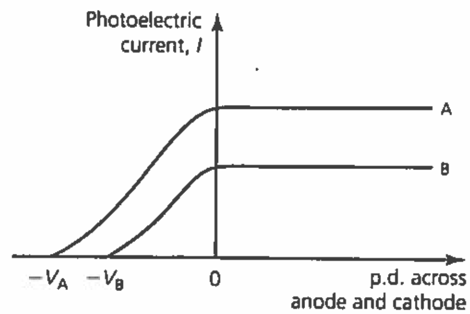
■ **Figure 12.7 Variation of photoelectric current with p.d. for radiation of three different intensities (same frequency)**

- **Frequency** – Figure 12.8 shows the photoelectric currents produced by radiation from two monochromatic sources of different frequencies, A and B, incident on the same metal.

The individual photons in radiation A must have more energy (than B) and produce photoelectrons with a higher maximum kinetic energy. We know this because a bigger reverse potential is needed to stop the more energetic photoelectrons produced by A.

No conclusion can be drawn from the fact that the current for A has been drawn higher than for B, because the intensities of the two radiations are not known. In the unlikely circumstances that the two intensities were equal, the maximum current for B would have to be higher than for A because the radiation from B must have more photons, because each photon has less energy than in A.

- **Metal used in the cathode** – Experiments confirm that when different metals are tested using the same frequency, the photoelectric effect is observed with some metals but not with others (for which the metal's work function is higher than the energy of the photons).



■ **Figure 12.8** Variation of photoelectric current with p.d. for radiation of two different frequencies

Light-emitting diodes (LEDs) can also be used to investigate the photoelectric effect (in 'reverse'). Electrons in an electric current passing through an LED undergo precise and identical energy transitions resulting in the emission of photons of the same single wavelength. If the potential difference across the LED is measured when it just begins to emit light, it can be used to determine a value for Planck's constant.

14 Make a copy of Figure 12.5 and add the results that would be obtained using radiation of a higher intensity (of the same frequency) incident on a metal that has a smaller work function.

15 Make a copy of Figure 12.8, line A only. Add to it a line showing the results that would be obtained with radiation of a higher frequency but with same number of photons every second incident on the metal.

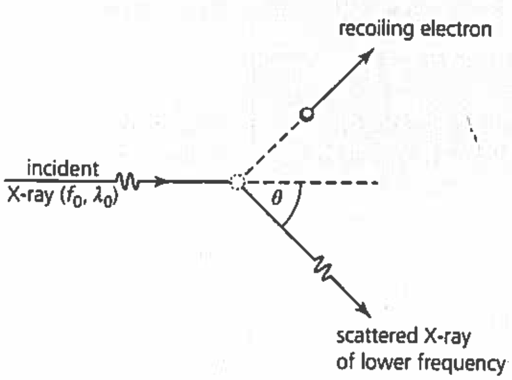
16 **a** Select five different metallic elements and then use the internet to research their work functions.
b Calculate the threshold frequencies of the five metals.

17 The voltage across an LED was increased until it just began to emit green light of wavelength 5.6×10^{-7} m. Determine a value for Planck's constant if the voltage was 2.2 V.

Additional Perspectives

The photon nature of electromagnetic radiation: the Compton effect

This effect, discovered in the USA in 1923 by Arthur Compton, provided further evidence for the photon nature of electromagnetic radiation.



■ **Figure 12.9** Compton scattering of X-rays

It was shown that X-rays could be scattered by electrons resulting in a reduced frequency because some of the photons' energy was passed to the scattered electron. See Figure 12.9.

Momentum (as always) is conserved in this interaction. This experiment shows that an X-ray behaves as a particle carrying momentum, $p = h/\lambda$, although it has no mass. This is explained by more advanced theory and it is only possible because photons travel at the speed of light. Similar comments apply to all other photons (light for example).

1 Use the Compton equation $\Delta\lambda = (h/m_e c)(1 - \cos\theta)$ to predict the change in wavelength associated with a scattering angle of 30°.

2 Use the equation to explain why Compton scattering of light is not significant.