

7

Atomic and nuclear physics

7.1 Atomic structure

Assessment statements

- 7.1.1 Describe a model of the atom that features a small nucleus surrounded by electrons.
- 7.1.2 Outline the evidence that supports a nuclear model of the atom.
- 7.1.3 Outline one limitation of the simple model of the nuclear atom.
- 7.1.4 Outline evidence for the existence of atomic energy levels.
- 13.1.8 Outline a laboratory procedure for producing and observing atomic spectra.
- 13.1.9 Explain how atomic spectra provide evidence for the quantization of energy in atoms.
- 13.1.10 Calculate wavelengths of spectral lines from energy level differences and vice versa.

The arrangement of charge in the atom

We already know that matter is made up of particles (atoms) and we used this model to explain the thermal properties of matter. We also used the idea that matter contains charges to explain electrical properties. Since matter contains charge and is made of atoms, it seems logical that atoms must contain charge. But how is this charge arranged?

There are many possible ways that charges could be arranged in the atom, but since atoms are not themselves charged, they must contain equal amounts of positive and negative. Maybe half the atom is positive and half negative, or perhaps the atom is made of two smaller particles of opposite charge?

The discovery of the electron by J.J. Thomson in 1897 added a clue that helps to solve the puzzle. The electron is a small negative particle that is responsible for carrying charge when current flows in a conductor. By measuring the charge-to-mass ratio of the electron, Thomson realised that the electrons were very small compared to the whole atom. He therefore proposed a possible arrangement for the charges as shown in Figure 7.1; this model was called the ‘plum pudding’ model. This model was accepted for some time until, under the direction of Ernest Rutherford, Geiger and Marsden performed an experiment that proved it could not be correct.

The Rutherford model

Rutherford’s idea was to shoot alpha particles at a very thin sheet of gold to see what would happen. In 1909, when this was happening, very little was known



What does it mean when we say we know these things? Do we know that this is true, or is it just the model that’s true?

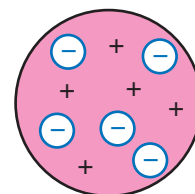


Figure 7.1 Thomson’s model, positive pudding with negative plums.



The electron is a fundamental particle with charge -1.6×10^{-19} C and mass 9.1×10^{-31} kg.

This is a good example of scientific method in practice.



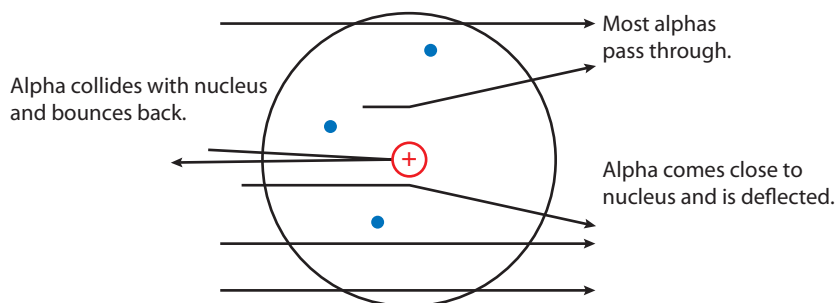
To see a simulation of Rutherford scattering, visit www.heinemann.co.uk, enter the express code 4426P and click on weblink 7.1.



about alpha particles – only that they were fast and positive. In accordance with normal scientific practice, Rutherford would have applied the model of the day so as to predict the result of the experiment. The current model was that the atom was like a small plum pudding, so a sheet of gold foil would be like a wall of plum puddings, a few puddings thick. Shooting alpha particles at the wall would be like firing bullets at a wall of plum puddings. If we think what would happen to the bullets and puddings, it will help us to predict what will happen to the alpha particles.

If you shoot a bullet at a plum pudding, it will pass straight through and out the other side (you can try this if you like). What actually happened was, as expected, most alpha particles passed through without changing direction, but a significant number were deflected and a few even came right back, as shown in Figure 7.2. This was so unexpected that Rutherford said ‘It was quite the most incredible event that ever happened to me in my life. It was almost as incredible as if you had fired a 15-inch shell at a piece of tissue paper and it came back and hit you.’ We know from our study of collisions that you can only get a ball to bounce off another one if the second ball is much heavier than the first. This means that there must be something heavy in the atom. The fact that most alphas pass through means that there must be a lot of space. If we put these two findings together, we conclude that the atom must have something heavy and small within it. This small, heavy thing isn’t an electron since they are too light; it must therefore be the positive part of the atom. This would explain why the alphas come back, since they are also positive and would be repelled from it.

Figure 7.2 Alpha particles deflected by a gold atom.



Some chemistry

An atom consists of a nucleus surrounded by a number of electrons. Different elements have different-sized nuclei and different numbers of electrons. To make the atom neutral the nucleus has the same charge (but positive) as all the electrons put together. The number of electrons in the neutral atom is equal to the atomic number of the element and defines the way that it combines with other elements.



The Bohr model

In 1913 Niels Bohr suggested that the nucleus could be like a mini solar system with the electrons orbiting the nucleus. This fits in very nicely with what we know about circular motion, since the centripetal force would be provided by the electric attraction between the electron and nucleus. The problem with this model is that as the electrons accelerate around the nucleus, they would continually radiate electromagnetic radiation; they would therefore lose energy causing them to spiral into the nucleus. This model therefore cannot be correct. One thing that the Bohr model did come close to explaining was the line spectrum for hydrogen.

The connection between atoms and light

There is a very close connection between matter and light. For example, if we give thermal energy to a metal, it can give out light. Light is an electromagnetic wave so must come from a moving charge; electrons have charge and are able to move, so it

would be reasonable to think that the production of light is something to do with electrons. But what is the mechanism inside the atom that enables this to happen? Before we can answer that question we need to look more closely at the nature of light, in particular light that comes from isolated atoms. We must look at isolated atoms because we need to be sure that the light is coming from single atoms and not the interaction between atoms. A single atom would not produce enough light for us to see, but low-pressure gases have enough atoms far enough apart not to interact.

Atomic spectra

To analyse the light coming from an atom we need to first give the atom energy; this can be done by adding thermal energy or electrical energy. The most convenient method is to apply a high potential to a low-pressure gas contained in a glass tube (a discharge tube). This causes the gas to give out light, and already you will notice (see Figure 7.3) that different gases give different colours. To see exactly which wavelengths make up these colours we can split up the light using a prism (or diffraction grating). To measure the wavelengths we need to know the angle of refraction; this can be measured using a spectrometer.

The hydrogen spectrum

Hydrogen has only one electron – so it is the simplest atom and the one we will consider first. Figure 7.4 shows the spectrum obtained from a low-pressure discharge tube containing hydrogen. The first thing you notice is that, unlike a usual rainbow that is continuous, the hydrogen spectrum is made up of thin lines. Light is a form of energy, so whatever the electrons do they must lose energy when light is emitted. If the colour of light is associated with different energies, then, since only certain energies of light are emitted, the electron must only be able to release certain amounts of energy. This would be the case if the electron could only have certain amounts of energy in the first place. We say the energy is *quantized*.

To help understand this, we can consider an analogous situation of buying sand. You can either buy sand loose or in 50 kg bags, and we say the 50 kg bags are quantized, since the sand comes in certain discrete quantities. So if you buy loose sand, you can get any amount you want, but if you buy quantized sand, you have to have multiples of 50 kg. If we make a chart showing all the possible quantities of sand you could buy, then they would be as shown on Figure 7.5; one is continuous and the other has lines.

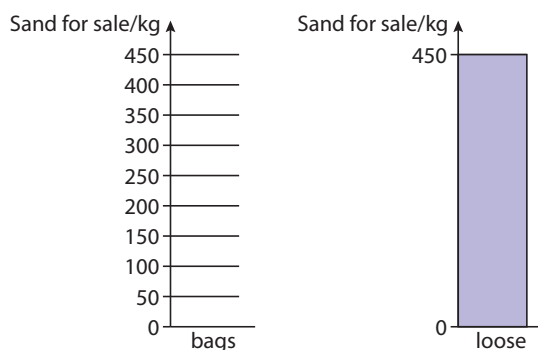


Figure 7.5 Ways of buying sand.

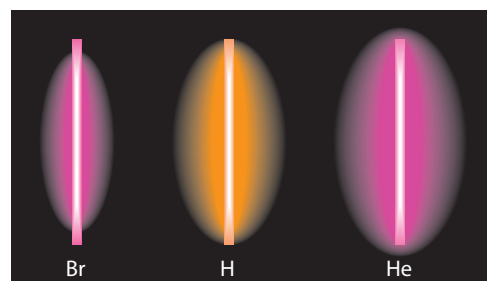


Figure 7.3 Discharge tubes containing bromine, hydrogen and helium.



Figure 7.4 The line spectrum for hydrogen.

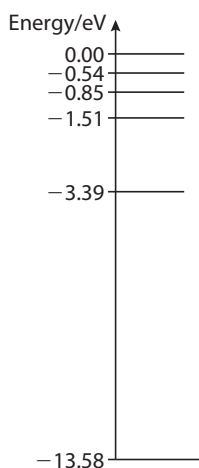


Figure 7.6 The electron energy levels of hydrogen.

If the electron in the hydrogen atom can only have discrete energies, then when it changes energy, that must also be in discrete amounts. We represent the possible energies on an energy level diagram (Figure 7.6), which looks rather like the sand diagram.

For this model to fit together, each of the lines in the spectrum must correspond to a different energy change. Light therefore must be quantized and this does not tie in at all with our classical view of light being a continuous wave that spreads out like ripples in a pond.

7.2 The quantum nature of light

Assessment statements

- 13.1.1 Describe the photoelectric effect.
- 13.1.2 Describe the concept of the photon, and use it to explain the photoelectric effect.
- 13.1.3 Describe and explain an experiment to test the Einstein model.
- 13.1.4 Solve problems involving the photoelectric effect.

Light definitely has wave-like properties; it reflects, refracts, diffracts and interferes. But sometimes light does things that we don't expect a wave to do, and one of these is the photoelectric effect.

The photoelectric effect

Consider ultraviolet light shining on a negatively charged zinc plate. Can the light cause the charge to leave the plate? To answer this question we can use the wave model of light, but we cannot see what is happening inside the metal, so to help us visualize this problem we will use an analogy.

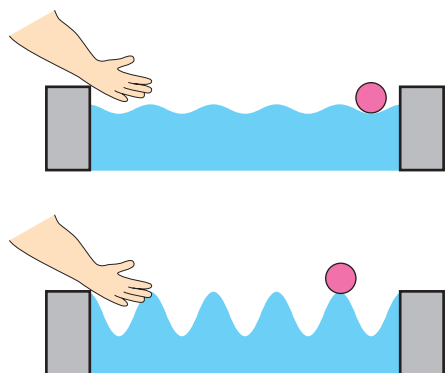
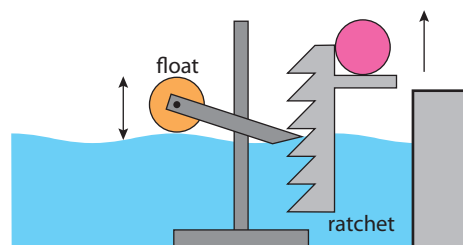


Figure 7.7

The swimming pool analogy

Imagine a ball floating near the edge of a swimming pool as in Figure 7.7. If you are at the other side of the swimming pool, could you get the ball out of the pool by sending water waves towards it? To get the ball out of the pool we need to lift it as high as the edge of the pool; in other words, we must give it enough PE to reach this height. We can do this by making the amplitude of the wave high enough to lift the ball. If the amplitude is not high enough, the ball will not be able to leave the pool unless we build a machine (as in Figure 7.8) that will collect the energy over a period of time. In this case, there will be a time delay before the ball gets out.

Figure 7.8



To relate this to the zinc plate, according to this model we expect:

- Electrons will be emitted only if the light source is very bright. (Brightness is related to amplitude of the wave.)
- If the source is dim we expect no electrons to be emitted. If electrons are emitted, we expect a time delay whilst the atoms collect energy from the wave.
- If we use lower frequency light, electrons will still be emitted if it is bright enough.

The zinc plate experiment

To find out if electrons are emitted or not, we can put the zinc plate on an electroscope and shine UV light on it as in Figure 7.9. If electrons are emitted charge will be lost and the electroscope leaf will fall. The results are not entirely as expected:

- The electroscope does go down indicating that electrons are emitted from the surface of the zinc plate.
- The electroscope leaf goes down even if the UV light is very dim. When very dim, the leaf takes longer to go down but there is no time delay before it starts to drop.
- If light of lower frequency is used, the leaf does not come down, showing that no electrons are emitted. This is the case even if very intense low frequency light is used.

These results can be explained if we consider light to be quantized.

Quantum model of light

In the quantum model of light, light is made up of packets called photons. Each photon is a section of wave with an energy E that is proportional to its frequency, f .

$$E = hf$$

where h is Planck's constant (6.63×10^{-34} J s).

The intensity of light is related to the number of photons, not the amplitude, as in the classical wave model. Using this model we can explain the photoelectric effect:

- UV light has a high frequency, so when photons of UV light are absorbed by the zinc, they give enough energy to the zinc electrons to enable them to leave the surface.
- When the intensity of light is low there are not many photons but each photon has enough energy to enable electrons to leave the zinc.
- Low frequency light is made of photons with low energy; these do not have enough energy to liberate electrons from the zinc. Intense low frequency light is simply more low energy photons, which still don't have enough energy.

If a swimming pool were like this then if someone jumped into the pool the energy they give to the water would stay together in a packet until it met another swimmer. When this happened the other swimmer would be ejected from the pool. Could be fun!

To get a deeper understanding of the photoelectric effect we need more information about the energy of the photoelectrons.

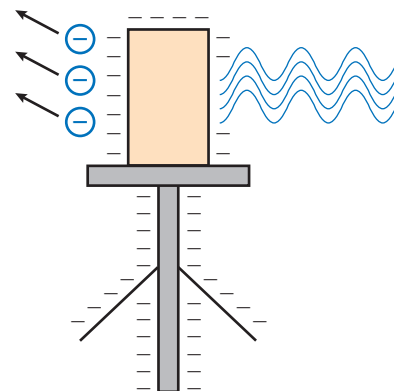


Figure 7.9 UV radiation is absorbed and electrons are emitted causing the gold leaf to fall.

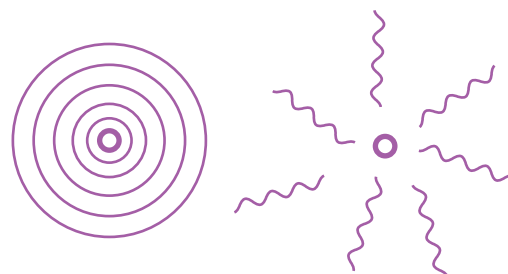


Figure 7.10 Light radiating, according to the wave model and the quantum model.

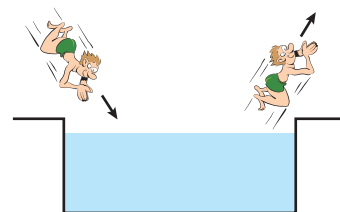


Figure 7.11 The quantum swimming pool.

Figure 7.12 The stopping potential stops the electrons from reaching the collector.

For a simulation of the photoelectric effect, visit www.heinemann.co.uk/hotlinks, enter the express code 4426P and click on weblink 7.2.

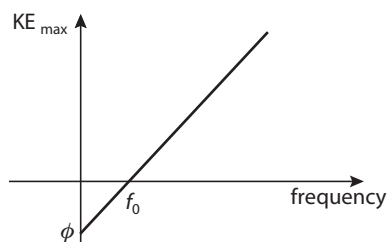
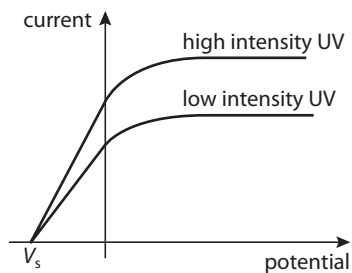
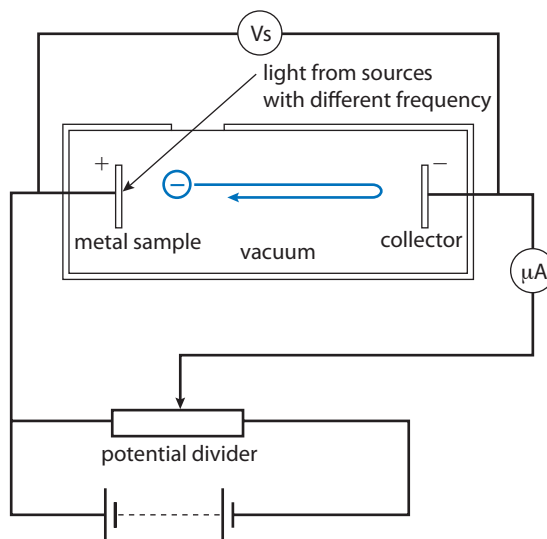


Figure 7.13 Graphs of current vs potential and maximum KE against frequency

● **Examiner's hint:** Exam questions can include many different graphs related to the photoelectric effect. Make sure you look at the axis carefully.

Millikan's photoelectric experiment

Millikan devised an experiment to measure the KE of photoelectrons. He used an electric field to stop the electrons completing a circuit and used that 'stopping potential' to calculate the KE. A diagram of the apparatus is shown in Figure 7.12.

Light from a source of known frequency passes into the apparatus through a small window. If the photons have enough energy, electrons will be emitted from the metal sample. Some of these electrons travel across the tube to the collector causing a current to flow in the circuit; this current is measured by the microammeter. The potential divider is now adjusted until none of the electrons reaches the collector (as in the diagram). We can now use the law of conservation of energy to find the KE of the fastest electrons.

Loss of KE = gain in electrical PE

$$\frac{1}{2}mv^2 = V_s e$$

So maximum KE, $KE_{\max} = V_s e$

The light source is now changed to one with different frequency and the procedure is repeated.

The graphs in Figure 7.13 show two aspects of the results.

The most important aspect of graph 1 is that for a given potential, increasing the intensity increases the current but doesn't change the stopping potential. This is because when the intensity is increased the light contains more photons (so liberates more electrons) but does not increase the energy (so V_s is the same).

Graph 2 shows that the maximum KE of the electrons is proportional to the frequency of the photons. Below a certain value, f_0 , no photoelectrons are liberated; this is called the *threshold frequency*.

Einstein's photoelectric equation

Einstein explained the photoelectric effect and derived an equation that relates the KE of the photoelectrons to the frequency of light.

Maximum photoelectron KE = energy of photon – energy needed to get photon out of metal

$$KE_{\max} = hf - \phi$$

ϕ is called the *work function*. If the photon has only enough energy to get the electron out then it will have zero KE, and this is what happens at the threshold frequency, f_0 . At this frequency

$$\text{KE}_{\text{max}} = 0 = hf_0 - \phi$$

so
$$\phi = hf_0$$

We can now rewrite the equation as

$$\text{KE}_{\text{max}} = hf - hf_0$$

Exercises

- A sample of sodium is illuminated by light of wavelength 422 nm in a photoelectric tube. The potential across the tube is increased to 0.6 V. At this potential no current flows across the tube. Calculate:
 - the maximum KE of the photoelectrons
 - the frequency of the incident photons
 - the work function of sodium
 - the lowest frequency of light that would cause photoelectric emission in sodium.
- A sample of zinc is illuminated by UV light of wavelength 144 nm. If the work function of zinc is 4.3 eV, calculate
 - the photon energy in eV
 - the maximum KE of photoelectrons
 - the stopping potential
 - the threshold frequency.
- If the zinc in Question 2 is illuminated by the light in Question 1, will any electrons be emitted?
- The maximum KE of electrons emitted from a nickel sample is 1.4 eV. If the work function of nickel is 5.0 eV, what frequency of light must have been used?

Quantum explanation of atomic spectra

We can now put our quantum models of the atom and light together to explain the formation of atomic spectra. To summarize what we know so far:

- Atomic electrons can only exist in certain discrete energy levels.
- Light is made up of photons.
- When electrons lose energy they give out light.
- When light is absorbed by an atom it gives energy to the electrons.

We can therefore deduce that when an electron changes from a high energy level to a low one, a photon of light is emitted. Since the electron can only exist in discrete energy levels, there are a limited number of possible changes that can take place; this gives rise to the characteristic line spectra that we have observed. Each element has a different set of lines in its spectrum because each element has different electron energy levels. To make this clear we can consider a simple atom with electrons in the four energy levels shown in Figure 7.14.

As you can see in the diagram there are six possible ways that an electron can change from a high energy to a lower one. Each transition will give rise to a photon of different energy and hence a different line in the spectrum. To calculate the photon frequency we use the formula

$$\text{Change in energy } \Delta E = hf$$



Equation of a straight line

The equation of a straight line is of the form $y = mx + c$ where m is the gradient and c is the y intercept. You should be able to see how the equation $\text{KE}_{\text{max}} = hf - \phi$ is the equation of the line in graph 2.

- **Hint:** You will find it easier to work in eV for Questions 2, 3 and 4.



The electronvolt

Remember 1 eV is the KE gained by an electron accelerated through a p.d. of 1 V.

$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$$

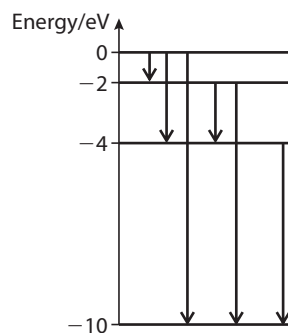


Figure 7.14

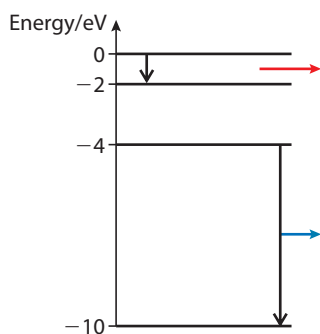


Figure 7.15

Comparing energies in eV

- The average KE of an atom in air at 20 °C is about 0.02 eV
a red light photon is 1.75 eV
a blue light photon is 3.1 eV.
- The energy released by one molecule in a chemical reaction is typically 50 eV.
- The energy released by one atom of fuel in a nuclear reaction is 200 MeV.

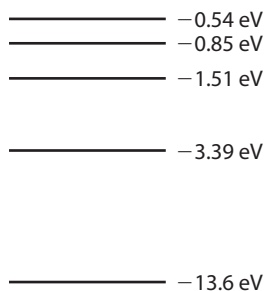


Figure 7.16

So the bigger energy changes will give lines on the blue end of the spectrum and low energies on the red end.

Example

A change from the -4 eV to the -10 eV level will result in a change of 6 eV. This is $6 \times 1.6 \times 10^{-19} = 9.6 \times 10^{-19}$ J

This will give rise to a photon of frequency given by

$$\Delta E = hf$$

$$\text{Rearranging gives } f = \frac{\Delta E}{h} = \frac{9.6 \times 10^{-19}}{6.63 \times 10^{-34}} = 1.45 \times 10^{15} \text{ Hz}$$

This is a wavelength of 207 nm which is UV.

Ionization

Ionization occurs when the electrons are completely removed from an atom, leaving a charged atom called an ion. This can happen if the atom absorbs a high energy photon or the electron could be 'knocked off' by a fast moving particle like an alpha. These interactions are quite different – when a photon interacts with an atom it is absorbed but when an alpha interacts it 'bounces off'.

Absorption of light

A photon of light can only be absorbed by an atom if it has exactly the right amount of energy to excite an electron from one energy to another. If light containing all wavelengths (white light) is passed through a gas then the photons with the right energy to excite electrons will be absorbed. The spectrum of the light that comes out will have lines missing. This is called an *absorption spectrum* and is further evidence for the existence of electron energy levels.

Exercises

Use the energy level diagram of Figure 7.16 to answer the following questions.

- How many possible energy transitions are there in this atom?
- Calculate the maximum energy (in eV) that could be released and the frequency of the photon emitted.
- Calculate the minimum energy that could be released and the frequency of the associated photon.
- How much energy would be required to completely remove an electron that was in the lowest energy level? Calculate the frequency of the photon that would have enough energy to do this.

7.3

The wave nature of matter

Assessment statements

- Describe the de Broglie hypothesis and the concept of matter waves.
- Outline an experiment to verify the de Broglie hypothesis.
- Solve problems involving matter waves.
- Outline the Heisenberg uncertainty principle with regard to position–momentum and time–energy.

The electron gun

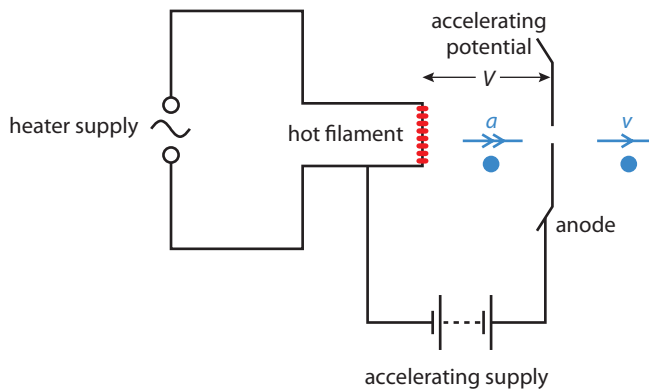
Imagine you have five identical boxes and each one contains one of the following: a large steel ball, a glass ball, air, sand, or a cat. You have to find out what is inside the boxes without opening them. One way of doing this is to fire a bullet at each.

Here are the results:

- 1 Shattering sound, contents – glass ball
- 2 Bounces back, contents – steel ball
- 3 Passes straight through, contents – air
- 4 Doesn't pass through, contents – sand

Well, the cat was lucky so we won't try shooting at the last box.

This idea is used a lot by physicists to find out what matter contains, but the projectile must be something much smaller than a bullet. In the Geiger and Marsden experiment discussed earlier, the projectile was an alpha particle. Electrons can also be used in this way but first they need to be accelerated, and to do this we use an electron gun, as shown in Figure 7.17.



The filament, made hot by an AC supply, liberates electrons which are accelerated towards the anode by the accelerating p.d. Electrons travelling in the direction of the hole in the anode pass through and continue with constant velocity.

We can calculate the speed of the electrons, using the law of conservation of energy.

Loss of electrical PE = gain in KE

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

$$v = \sqrt{\frac{2Ve}{m}}$$

Detecting electrons

You can't see electrons directly, so you need some sort of detector to find out where they go. When electrons collide with certain atoms they give the atomic electrons energy (we say the electrons are 'excited'). When the atomic electrons go back down to a lower energy level, they give out light. This is called *phosphorescence* and can be used to see where the electrons land. Zinc sulphide is one such substance; it is used to coat glass screens so that light is emitted where the electrons collide with the screen. This is how the older types of TV screens work.



This is an example of how scientists use experimental evidence to build models of things they can't see. Note that in these examples you don't just need a bullet, you also need a detector. What if you didn't notice the sound of breaking glass? You would have to have some idea that this was going to happen or you might not have been listening.

Figure 7.17 A simple electron gun.



Thermionic emission

In this case atomic electrons gain enough energy from thermal excitation to leave the surface of the metal.

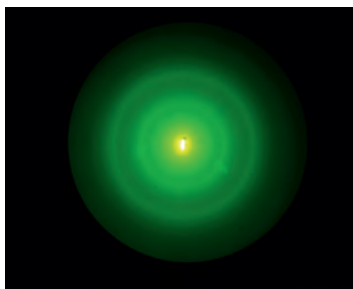


KE in eV

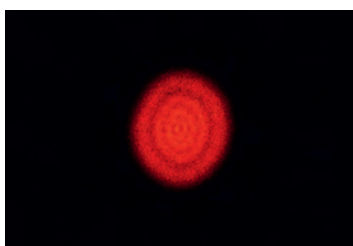
The KE of the electrons in eV is numerically the same as the accelerating p.d.
If p.d. = 200 V
KE = 200 eV



The aurora borealis is caused when charged particles from the Sun excite atoms in the atmosphere.



Diffraction of electrons by a graphite film.



Diffraction of light by a small circular aperture.

Electron diffraction

If a beam of electrons is passed through a thin film of graphite, an interesting pattern is observed when they hit a phosphor screen. The pattern looks very much like the diffraction pattern caused when light is diffracted by a small circular aperture. Perhaps the electrons are being diffracted by the atoms in the graphite. Assuming this to be true, we can calculate the wavelength of the wave that has been diffracted. But diffraction is a wave-like property, so what is it about an electron that behaves like a wave?

The de Broglie hypothesis

In 1924 Louis de Broglie proposed that 'all matter has a wave-like nature' and that the wavelength of that wave could be found using the equation:

$$\lambda = \frac{h}{p}$$

where p is the momentum of the particle.

Using this equation we can calculate the momentum of the electrons used in the electron diffraction experiment.

If the accelerating p.d. is 500 V then the velocity of an accelerated electron is

$$v = \sqrt{\frac{2 \times 500 \times 1.6 \times 10^{-19}}{9.1 \times 10^{-31}}} = 1.3 \times 10^7 \text{ m s}^{-1}$$

Momentum = $mv = 1.2 \times 10^{-23} \text{ N s}$

So the wavelength, $\lambda = 5.5 \times 10^{-11} \text{ m}$

This is the correct size to give a wavelength that would cause the observed diffraction pattern. But what is it about the electron that has wave-like properties?

Probability waves

The de Broglie hypothesis makes us think about the nature of particles like electrons in a very different way. Classically we think of an electron as a very small ball. Small balls are very simple to model. If we know where a ball is now and what its momentum is, we can use the *suvat* equations to work out exactly where it will be in the future. According to the de Broglie hypothesis, matter isn't like that; the position of a particle is governed by a wave function, not the *suvat* equations; this wave function gives the probability of finding the particle. When the particle passes through a small opening, the wave diffracts, giving the particle the possibility to be in places we wouldn't expect. This is only evident for very small particles because large particles cannot pass through anything small enough for diffraction to take place. (Remember diffraction is only noticeable when the opening is about the same size as the wavelength.)

Consider electron A on a crash course for electron B as shown in Figure 7.18. Classically we can calculate exactly when they collide. We know when this takes place because B will start to move.

What the de Broglie hypothesis says is that the position of A is given by a probability distribution that is defined by the wave travelling in the same direction. As the probability wave passes B the probability of an interaction becomes higher and higher, until at some moment B will move. We can't say when exactly this will happen, just that it happens some time as the wave passes B. So the electron

isn't a little ball at all – it is simply a region of space that has certain properties (charge and mass). These properties define the way that this region of space can interact with other regions and the probability of an interaction is given by a wave equation.

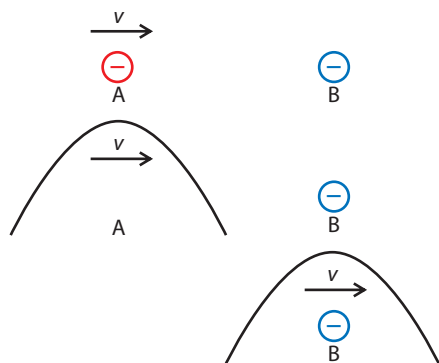


Figure 7.18 Electron A approaches electron B.

Explaining diffraction

Using the de Broglie hypothesis, we can now attempt to explain electron diffraction. An electron is travelling toward a very narrow slit. As it travels, its wave function precedes it. The wave function will pass through the slit, mapping out the probable positions of the electron. This wave function is diffracted by the slit, which makes it possible for the electron to appear in the maxima of the pattern. If lots of electrons pass through the slit then they will all land somewhere in the maxima of the pattern, forming the electron diffraction pattern seen in the previous photo.

Exercises

- 9 An electron is accelerated by a p.d. of 100V. Calculate its
 - (a) KE in eV
 - (b) KE in joules
 - (c) de Broglie wavelength.
- 10 Calculate the de Broglie wavelength for a car of mass 1000 kg travelling at 15 m s^{-1} . Why won't you ever see a car diffract?

Heisenberg's uncertainty principle

To find the path of a particle we need to know its position and momentum. Let us try to limit the position of an electron in a parallel beam of electrons all with equal momentum. We can do this by passing it through a narrow slit as in Figure 7.19. The uncertainty in its position Δx as it passes through the slit is therefore equal to the slit width. If the slit is wide, then the electron will pass straight through without diffracting, so we know its future direction and hence its momentum, but the uncertainty in position is large. To reduce this uncertainty, we can reduce the slit width, but if we do that it will diffract. This gives an increased number of possibilities for its path, so the uncertainty in momentum increases. This no-win situation is called the *Heisenberg uncertainty principle* and can be expressed by the equation:

$$\Delta p \Delta x \geq \frac{h}{4\pi}$$

A similar relationship exists when you try to define energy and time.

$$\Delta E \Delta t \geq \frac{h}{4\pi}$$

The Davidson-Germer experiment

In this experiment a beam of electrons was reflected off a nickel crystal. The angle of the maximum intensity of reflected electrons can be explained in terms of the constructive interference of de Broglie waves reflected off different layers of atoms. This supports the de Broglie hypothesis.

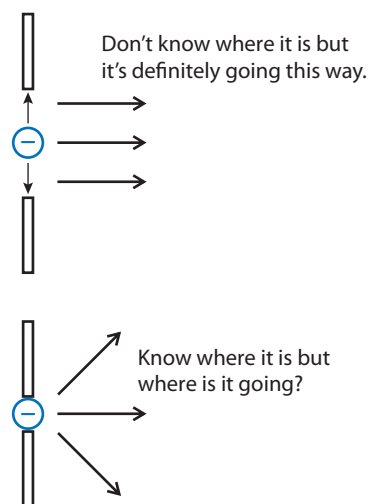


Figure 7.19 We can't know both momentum and position accurately.

It is important to realise that the uncertainty principle is not just about measurement – it is about the way things are.

7.4 Quantum models of the atom

Assessment statements

- 13.1.11 Explain the origin of atomic energy levels in terms of the 'electron in a box' model.
- 13.1.12 Outline the Schrödinger model of the hydrogen atom.

Returning to the atomic model, we know that atomic electrons can only have discrete energy levels, which are different for each element. Treating atomic electrons as waves gives us an insight into the reason why electrons can only have certain discrete energy levels.

The electron in a box

The probability wave that defines the position of a free electron can be thought of as a wave travelling along a string. As a peak moves down the string, the most likely position of the electron moves with it. An atomic electron is not free to move outside the atom, and to model this we can think of a wave trapped in a short length of string clamped at both ends (like a guitar string). When we trap a wave in a string it reflects backwards and forwards, creating a standing wave. This standing wave must have nodes at either end, so can only have certain frequencies, the harmonics, as shown in Figure 7.20. This is very similar to the situation with an atomic electron that can only have certain discrete energies. By treating an atomic electron as a probability wave trapped in a box, we can develop a quantum model of the atom.

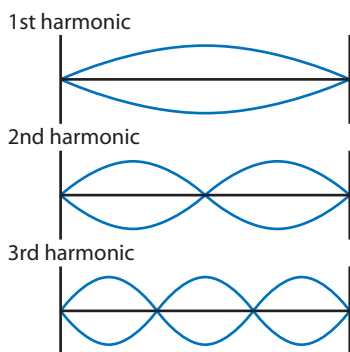


Figure 7.20

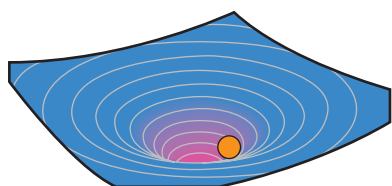


Figure 7.21 An electron trapped in a potential well.

To pull an electron out of an atom you would need to exert a force to oppose the electric attraction between the electron and the nucleus. We can think of the electron as a ball in a potential well, as shown in Figure 7.21; the shape of the sides of the well is determined by the electric force. This is rather complicated, so to make life simpler, we will consider the potential well to be a square box.

The wavelength of the electron's probability wave is governed by the size of the box, the longest possible wavelength being $2L$ as shown in Figure 7.23.

$$\text{The de Broglie wavelength, } \lambda = \frac{h}{p} = \frac{h}{mv}$$

$$\text{so } v = \frac{h}{m\lambda}$$

$$\text{The KE of the electron} = \frac{1}{2}mv^2$$

$$\text{Substituting for } v \\ \text{gives KE} = \frac{1}{2}m \times \frac{h^2}{m^2\lambda^2} = \frac{h^2}{2\lambda^2 m}$$

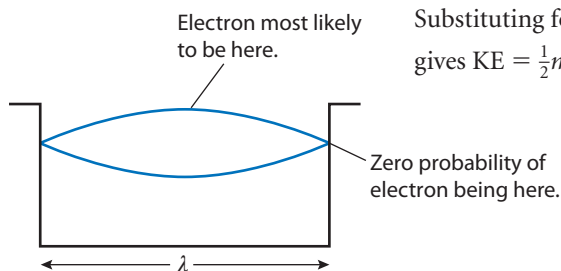


Figure 7.22 The probability wave confined to a square box.

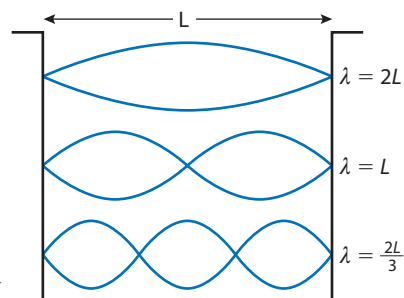


Figure 7.23

We know that the wavelength can have many values, as in Figure 7.23:

$$2L, \frac{2L}{2}, \frac{2L}{3}, \frac{2L}{4}$$

All possible waves can be defined by the equation $\lambda = \frac{2L}{n}$ where n is an integer (1,2,3....)

Substituting into the equation for KE gives

$$\text{KE} = \frac{n^2 h^2}{8mL^2}$$

So by treating the electron as a wave trapped in a box, we find that the energy can only be certain discrete values. From this we can predict the energy levels of the hydrogen atom and hence the possible energy level changes that give rise to the atomic spectra. Unfortunately this does not give the right result, as the model is a bit too simple. However, we are on the right track.

Schrödinger's model

Schrödinger realised that the probability that the electron is in a particular position in the atom is defined by the square of a wave function, but that wave function was not as simple as the sine wave used previously. The wave function is called *Schrödinger's equation* and is denoted by the Greek letter ψ . The probability of finding the electron is therefore ψ^2 . By solving the equation for this wave trapped in the potential well of the atom, Schrödinger calculated the correct values for the possible electron energies. His model also predicted that some energy transitions were more likely, explaining why some spectral lines are brighter than others.

If we plot the probability function for the different energies of the electron in hydrogen we see that for a given energy there are some places that the electron is more likely to be than others, but the electron is not stationary – it is moving about very quickly. So if we could watch the electron, it would appear like a cloud, even though there is only one electron. For the hydrogen atom, some of these clouds form spheres of different radius, the larger energy clouds having bigger radius.

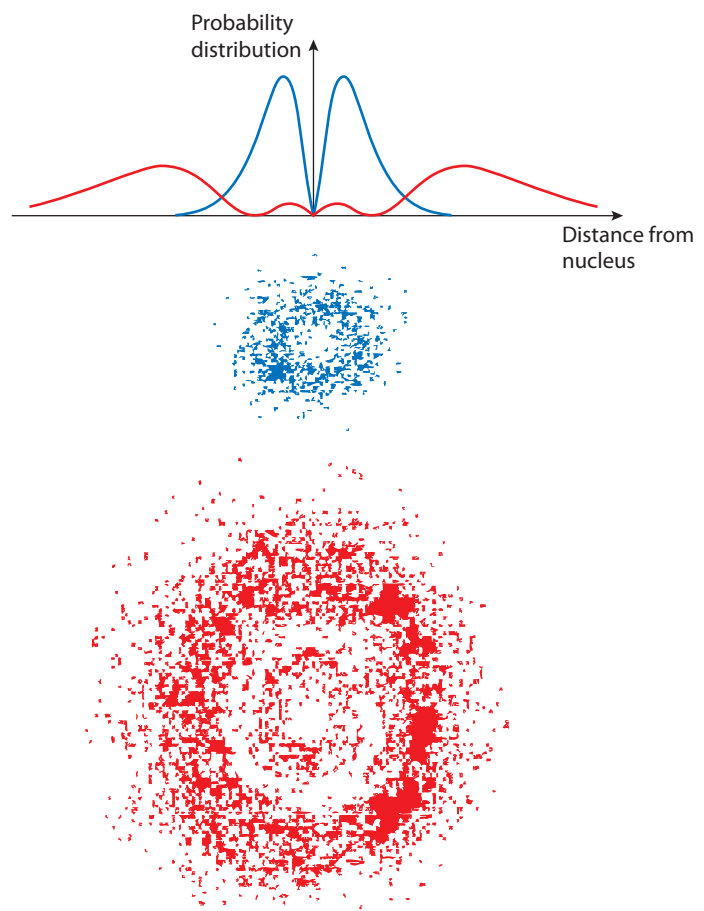


Figure 7.24 The probability densities and electron clouds for two of the possible electron energies for the hydrogen atom.

7.5 Nuclear structure

Assessment statements

- 7.1.5 Explain the terms nuclide, isotope and nucleon.
- 7.1.6 Define nucleon number A , proton number Z and neutron number N
- 7.1.7 Describe the interactions in a nucleus.
- 7.3.3 Define the term unified atomic mass unit.
- 7.3.4 Apply the Einstein mass–energy equivalence relationship.
- 7.3.5 Define the concepts of mass defect, binding energy and binding energy per nucleon.
- 7.3.6 Draw and annotate a graph showing the variation with nucleon number of the binding energy per nucleon.
- 7.3.7 Solve problems involving mass defect and binding energy.
- 13.2.2 Describe how the masses of nuclei may be determined using a Bainbridge mass spectrometer.
- 13.2.1 Explain how the radii of nuclei may be estimated from charged particle scattering experiments.

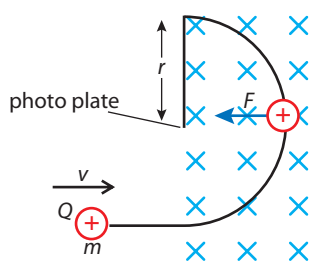


Figure 7.25 Deflection chamber of a mass spectrometer.

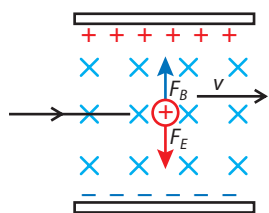


Figure 7.26 Velocity selector of a mass spectrometer.

Mass of the nucleus

The mass of a nucleus can be measured using a mass spectrometer. The principle behind the operation of a mass spectrometer is that if nuclei of the same charge and velocity are projected at right angles to a region of uniform magnetic field, the radius of the resulting circular path will be proportional to their mass. Figure 7.25 shows this situation.

The centripetal force is provided by the magnetic force, so we can write the equation:

$$\frac{mv^2}{r} = BQv$$

Rearranging this gives $m = \frac{BQr}{v}$

So the mass is proportional to the radius, provided the velocity and charge are the same.

In practice, it is difficult to remove all the electrons from an atom, leaving just the nucleus, but it is enough to just remove one. This leaves the atom with a charge of $+e$, the extra mass of the electrons making little difference. If we have a gas of ionized atoms then we can increase their velocity by heating. However, as we know from thermal physics, the atoms of a gas do not all have the same velocity. To select atoms with the same velocity, a combination of electric and magnetic fields is used (as shown in Figure 7.26).

An ion entering the velocity selector will experience two forces: magnetic force $F_B = BQv$ (upwards) and electric force $F_E = EQ$ (downwards).

These forces will be balanced if $F_E = F_B$, and in this case the particle will continue with a constant velocity.

For the forces to be balanced, $BQv = EQ$

This is only true when $v = \frac{E}{B}$ so all the ions that continue in a straight line must have velocity equal to $\frac{E}{B}$.

To detect the ions, a photographic plate is positioned as in Figure 7.25. When ions land on the plate, they change the chemical structure of the plate, which results in a small black dot when the plate is developed. Counting the number of dots enables the number of ions to be determined.

Exercises

Assume all ions have a charge of $+e$.

- 11 Considering the mass spectrometer in Figure 7.27, find
- the velocity of the ions coming through the velocity selector
 - the mass of an ion with a deflection radius of 6 cm.
- 12 An ion of mass 5.1×10^{-26} kg passes into the deflection chamber of the mass spectrometer in Question 11. What is its radius of deflection?

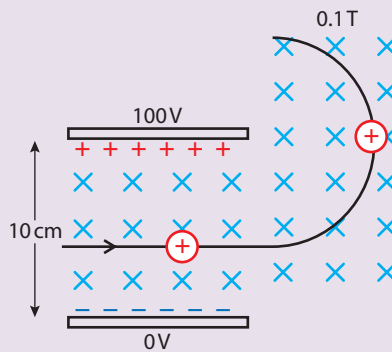
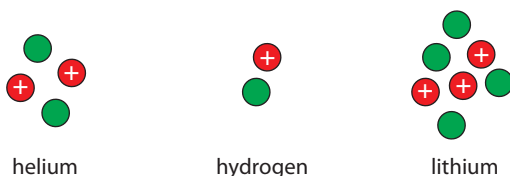


Figure 7.27

By measuring the masses of all known nuclei it was discovered that they all have a mass that is a multiple of the same number. This led to the idea that the nucleus is made up of smaller particles. In the same way, if you measured the mass of many boxes of apples and found that the mass of every box was a multiple of 100 g, you might conclude that the mass of each apple was 100 g.

Charge of the nucleus

It is also possible to measure the charge of all known nuclei. Each nucleus is found to have a charge that is a multiple of the charge on the electron, but positive. It would be reasonable to think that each of the particles in the nucleus must have a positive charge, but that makes the charge too big. It is therefore suggested that there are two types of particle in the nucleus, protons with positive charge and neutrons with no charge.



Nuclear masses are measured in unified mass units (u).
 Proton mass = 1.0078 u.
 Neutron mass = 1.0086 u.
 1 u is the mass of $\frac{1}{12}$ of the nucleus of a carbon-12 isotope.

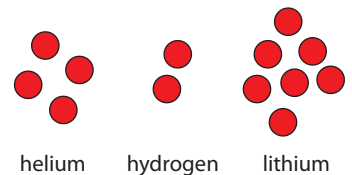


Figure 7.28 Some different sized nuclei.



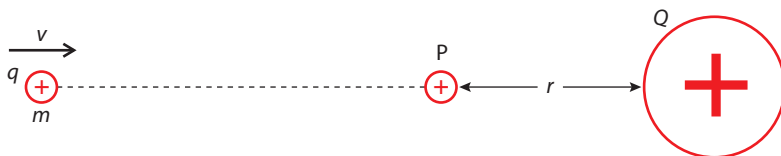
Masses and charges
 Proton mass = 1.672×10^{-27} kg
 Neutron mass = 1.675×10^{-27} kg
 Proton charge = $+1.6 \times 10^{-19}$ C
 Neutron charge = 0

Figure 7.29 Nuclei showing protons and neutrons.

Size of the nucleus

The size of the nucleus can be determined by conducting a similar experiment to the alpha scattering experiment of Geiger and Marsden. The alpha particles that come straight back off the gold foil must have approached a nucleus head-on following a path as shown in Figure 7.30.

Figure 7.30



Applying the law of conservation of energy to this problem, we can deduce that at point P, where the alpha particle stops, the original KE has been converted to electrical PE.

$$\frac{1}{2}mv^2 = \frac{kQq}{r}$$

where $Q =$ the charge of the nucleus ($+Ze$)
and $q =$ the charge of the alpha ($+2e$)

The KE of the alpha can be calculated from the change in the mass of a nucleus when it is emitted (more about this later), so knowing this, the distance r can be calculated.

To determine the size of the nucleus, faster and faster alphas are sent towards the nucleus until they no longer come back. The fastest ones that return have got as close to the nucleus as possible.

This is just an estimate, especially since (as is the case for all particles) the position of the particles that make up the nucleus is determined by a probability function. This will make the definition of the edge of the nucleus rather fuzzy.

When Geiger and Marsden did their gold foil experiment they didn't have alphas with enough energy to get close enough to the gold nucleus to give a very accurate value for its radius. They did however get quite close to aluminium nuclei.



Exercise

- 13** It is found that alpha particles with KE 7.7 MeV bounce back off an aluminium target. If the charge of an aluminium nucleus is $+2.1 \times 10^{-18} \text{ C}$, calculate:
- the velocity of the alpha particles (they have a mass of $6.7 \times 10^{-27} \text{ kg}$)
 - the distance of closest approach to the nucleus.

Some quantities and terms related to the nucleus

- **Nucleon**

The name given to the particles of the nucleus (proton, neutron).

- **Nuclide**

A combination of protons and neutrons that form a nucleus.

- **Isotopes**

Nuclei with the same number of protons but different numbers of neutrons (as shown in Figure 7.31).

- **Nucleon number (A)**

The number of protons plus neutrons in the nucleus (e.g. lithium-7). This will be different for different isotopes of the same element.

- **Proton number (*Z*)**

The number of protons in the nucleus (e.g. for lithium this is 3). This is always the same for a given element.

- **Neutron number (*N*)**

The number of neutrons in a nucleus.

- **Symbol for a nucleus**

A nuclide can be represented by a symbol that gives details of its constituents,

e.g. ${}^7_3\text{Li}$ 7 – nucleon number
 3 – proton number

Exercises

14 How many protons and neutrons are there in the following nuclei?

(a) ${}^{35}_{17}\text{Cl}$

(b) ${}^{58}_{28}\text{Ni}$

(c) ${}^{204}_{82}\text{Pb}$

15 Calculate the charge in coulombs and mass in kg of a ${}^{54}_{26}\text{Fe}$ nucleus.

16 An isotope of uranium (U) has 92 protons and 143 neutrons. Write the nuclear symbol for this isotope.

17 Describe the structure of another isotope of uranium, having the symbol ${}^{238}_{92}\text{U}$.

The nuclear force (strong force)

If a metal wire is heated it will readily emit electrons. However, you would have to heat it to temperatures approaching the temperature of the Sun before any neutrons or protons broke free. The fact that it requires a lot of energy to pull the nucleus apart implies that the force holding the nucleons together is a very strong force. It is therefore not surprising that when particles do come out of the nucleus, they have very high energy. We know that protons are positive, so they must repel each other. However, the nuclear force is so much bigger than the electric force that the nucleons are not pushed apart.

Although the nuclear force is strong, different nuclei do not attract each other. This means that the force must be very short range, unlike the electric force that extends forever.

Since protons repel each other, we might expect that the nuclear force would be stronger between protons than between neutrons. If this were the case, then nuclides with more neutrons would be pulled together more tightly than those with a lot of protons. But since all nuclei have the same density, this is not the case. So the nuclear force is very strong, short range and the same for all nucleons.

Binding energy

The binding energy is defined as the amount of work required to pull apart the constituents of a nucleus.

If work is done, then energy must have been transferred to the nucleons. However, they aren't moving so haven't any KE, and they aren't in a field, so don't have PE.

Where has the energy gone?

Einstein solved this problem with his famous equation

$$E = mc^2$$

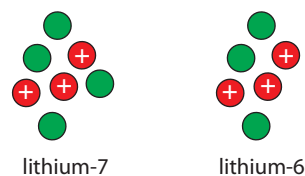


Figure 7.31 Two isotopes of lithium.

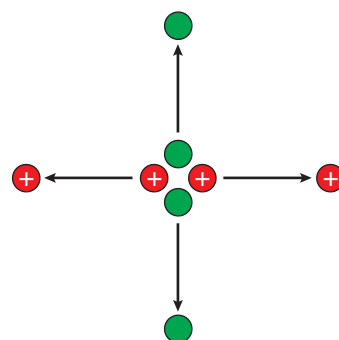


Figure 7.32 Work must be done to pull a nucleus apart; if a nucleus is put together then energy must be released.



We measure nuclear energies in MeV. 1 MeV is the KE an electron would gain if accelerated through a p.d. of 1 000 000 V.

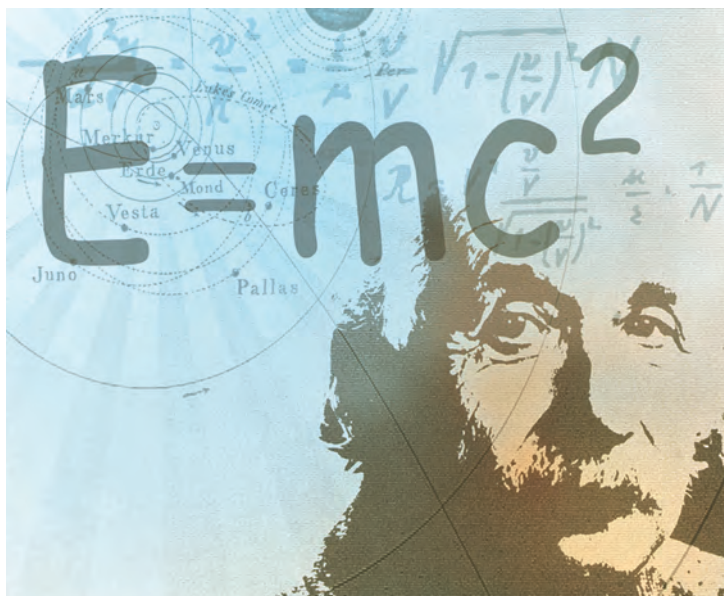
The energy has been converted into mass. This would imply that the mass of the particles when they are apart is greater than when they are together. If a nucleus has a large binding energy then it will require a lot of work to pull it apart – we say it is stable.

$E = mc^2$ is probably the most famous formula in the world – and Albert Einstein, definitely the most famous physicist.

Mass equivalents

$$1 \text{ kg} = 9 \times 10^{16} \text{ J}$$

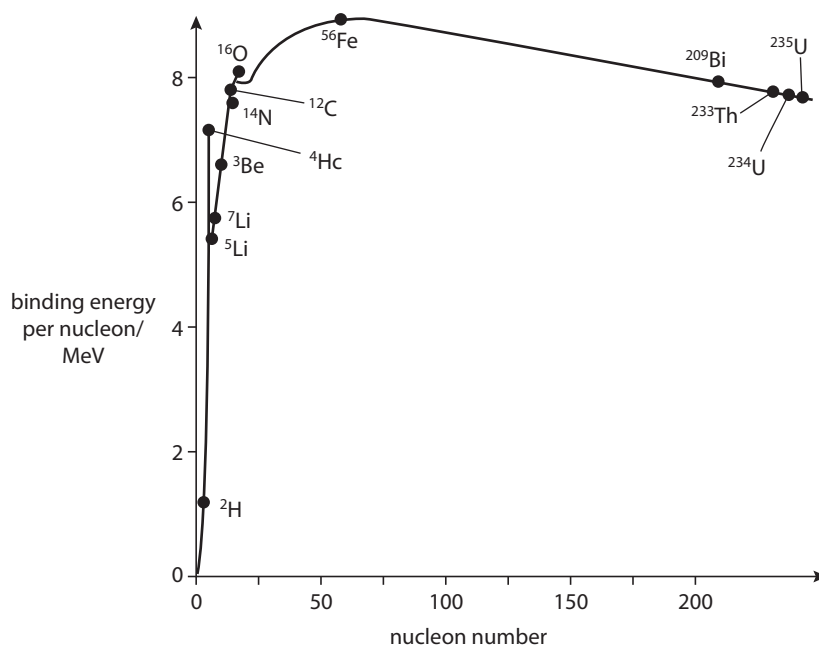
$$1 \text{ u} = 931.5 \text{ MeV}$$



The binding energy curve

It is possible to calculate the binding energy (BE) of a nucleus by finding the difference between the mass of the nucleus and the mass of the parts – this is called the *mass defect*. We can then plot a graph of BE per nucleon against nucleon number for all known nuclei. The result is shown below.

Figure 7.33 Graph of BE/nucleon vs nucleon number.



From this chart we can see that some nuclei are more stable than others. Iron is in fact the most stable, which is why there is so much of it. In nuclei where there are a lot of protons the electric repulsion tends to push them apart. This means that

large nuclei are less stable, and there are no nuclei that have more than about 300 nucleons.

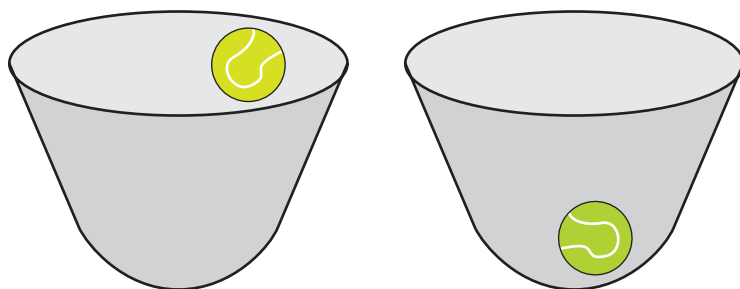


Figure 7.34 To lift a ball out of the bottom of a bowl we need to do work. This is just like the BE of the nucleus. When the ball is in the bowl, it does not have this energy – it is what was lost when it rolled to the bottom.

We have found that all physical systems will, if possible, reach a position of lowest possible energy. So, if possible, a nucleus will change into one with lower energy – this means that a nucleus will change to one with more BE. Remember, BE is released when the nucleus is formed, so changing to a higher BE means energy is released.

As we can see from the section of the graph shown in Figure 7.35, ^{233}Th has a higher BE than ^{235}U . It would therefore be energetically favourable for ^{235}U to change into ^{233}Th . However this may not be possible.

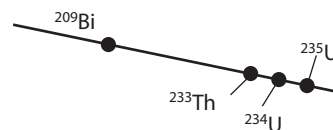


Figure 7.35 A section of the BE curve.

Nuclear masses			
Z	Symbol	A	Mass (u)
1	H	1	1.0078
1	D	2	2.0141
2	He	3	3.0160
3	Li	6	6.0151
4	Be	9	9.0122
7	N	14	14.0031
17	Cl	35	34.9689
26	Fe	54	53.9396
28	Ni	58	57.9353
36	Kr	78	77.9204
38	Sr	84	83.9134
56	Ba	130	129.9063
82	Pb	204	203.9730
86	Rn	211	210.9906
88	Ra	223	223.0185
92	U	233	233.0396

The table gives a selection of nuclear masses measured in u. With these values it is possible to calculate the binding energy of the nucleus.



Database

For a fully searchable database of all nuclides, visit www.heinemann.co.uk/hotlinks, enter the express code 4426P and click on Weblink 7.3. Click on the element in the Periodic Table to find nuclear data.

Worked example

Calculate the binding energy of iron (Fe).

Nucleon	Mass (u)
Proton	1.00782
Neutron	1.00866

Solution

From the table we can see that the iron nucleus is made of 26 protons and $(54 - 26) = 28$ neutrons.

The total mass of the nucleons that make up iron is therefore:

$$26 \times \text{mass of a proton} + 28 \times \text{mass of a neutron} = 54.4458 \text{ u}$$

But from the table, the mass of iron is 53.9396 u.

The difference between these two values is 0.5062 u.

But $1 \text{ u} = 931.5 \text{ MeV}$, so this is equivalent to an energy of $0.5062 \times 931.5 \text{ MeV}$

$$\text{BE} = 471.5 \text{ MeV}$$

Since there are 54 nucleons in iron then the binding energy per nucleon is

$$\frac{471.5}{54} = \mathbf{8.7 \text{ MeV/nucleon}}$$

Exercises

- 18** Find uranium in the table of nuclear mass.
- How many protons and neutrons does uranium have?
 - Calculate the total mass of the protons and neutrons that make uranium.
 - Calculate the difference between the mass of uranium and its constituents (the mass defect).
 - What is the binding energy of uranium in MeV?
 - What is the BE per nucleon of uranium?
- 19** Enter the data from the table into a spreadsheet. Add formulae to the spreadsheet to calculate the binding energy per nucleon for all the nuclei and plot a graph of BE/nucleon against nucleon number.

Remember: 1 u is equivalent to 931.5 MeV.

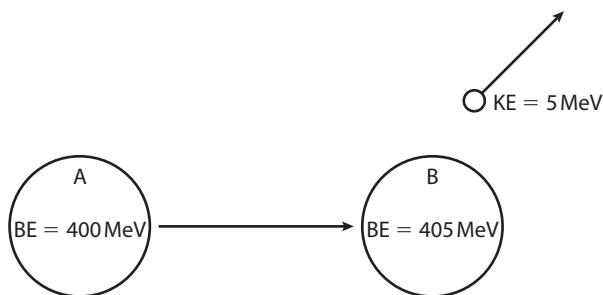


7.6 Radioactive decay

Assessment statements

- 7.2.1 Describe the phenomenon of natural radioactive decay.
- 7.2.2 Describe the properties of α - and β -particles and γ -radiation.
- 7.2.3 Describe the ionizing properties of α - and β -particles and γ -radiation.
- 7.2.4 Outline the biological effects of ionizing radiation.
- 7.2.5 Explain why some nuclei are stable while others are unstable.
- 13.2.3 Describe one piece of evidence for the existence of nuclear energy levels.
- 13.2.4 Describe β^+ decay, including the existence of the neutrino.

The nucleus can lose energy by emitting radiation. There are three types of ionizing radiation: alpha, beta and gamma. Alpha and beta emissions result in a change in the number of protons and neutrons. Gamma is a form of electromagnetic radiation, similar to X-rays. When a nucleus changes in this way it is said to *decay*.



If nucleus A were made from its constituent protons and neutrons, 400 MeV of energy would be released, but making B would release 405 MeV. Therefore if A changes to B, 5 MeV of energy must be released. This excess energy is given to the particle emitted.

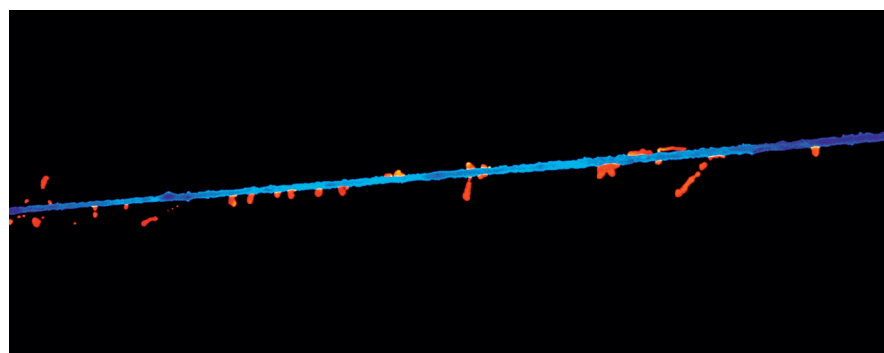
Figure 7.36 A nucleus can emit radiation only if the result is an increase in binding energy.

Alpha radiation (α)



Alpha particles have energies of about 5 MeV. To knock an electron out of an atom requires about 10 eV, so alpha particles can ionize a lot of atoms before they lose all their KE. This property makes them very easy to detect using a Geiger-Muller tube, photographic paper or cloud chamber. It also makes them harmful since ionizing atoms of human tissue causes damage to the cells similar to burning. Due to their high reactivity and ionization, alpha particles have a range of only a few centimetres in air and cannot penetrate paper.

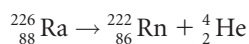
Figure 7.37 An alpha particle is a helium nucleus (2 protons + 2 neutrons).



Cloud chamber track of an alpha particle. These are like mini vapour trails. The red lines are some of the electrons that the alpha has knocked off atoms in the chamber.

Effect on nucleus

When a nucleus emits an alpha particle it loses 2 protons and 2 neutrons. The reaction can be represented by a nuclear equation. For example, radium decays into radon when it emits an alpha particle.



4 nucleons are emitted, so the nucleon number is reduced by 4.
2 protons are emitted, so the proton number is reduced by 2.

Energy released

When radium changes to radon the BE is increased. This leads to a drop in total mass, this mass having been converted to energy.

Mass of radium > (mass of radon + mass of alpha)

$$\text{Energy released} = \{\text{mass}_{\text{Ra}} - (\text{mass}_{\text{Rn}} + \text{mass}_{\text{alpha}})\}c^2$$

$$\text{mass}_{\text{Ra}} = 226.0254 \text{ u}$$

$$\text{mass}_{\text{Rn}} = 222.0176 \text{ u}$$

$$\text{mass}_{\text{He}} = 4.002602 \text{ u}$$

$$\text{Change in mass} = 0.005198 \text{ u}$$

This is equivalent to energy of $0.005198 \times 931.5 \text{ MeV}$

$$\text{Energy released} = 4.84 \text{ MeV}$$

Alpha energy

When an alpha particle is ejected from a nucleus, it is like an explosion where a small ball flies apart from a big one, as shown in Figure 7.38. An amount of energy is released during the explosion, which gives the balls the KE they need to fly apart.

Applying the principle of conservation of momentum:

momentum before = momentum after

$$0 = 1 \times v_2 - 800 \times v_1$$

$$\text{Therefore } v_1 = \frac{v_2}{800}$$

The velocity of the big ball is therefore much smaller than the small one, which means that the small ball gets almost all the kinetic energy. The energy available when alpha particles come from a certain nuclear reaction is constant; it can be calculated from the change in mass. We can see this if we look at the cloud chamber tracks in the photo. As the particles pass through the vapour they ionize vapour atoms, each ionization leading to a loss in energy. The more KE the particle has, the more ionizations it can make; this leads to a longer track. We can see in the photo that most of the tracks are the same length, which means all the alphas had the same KE, say 5 MeV. However if we look carefully at the photo, we can see there is one track that is longer. From the length of the track we can calculate it has energy of 8 MeV. If we calculate the energy released when the nucleus decays, we find it is 8 MeV, which means that when the nucleus is giving out the alphas with low energy, it is remaining in an excited state. This energy will probably be lost at a later time by the emission of gamma radiation. The nucleus seems to have energy levels like atomic electrons. Figure 7.39 shows the energy levels that could cause the change in this example.

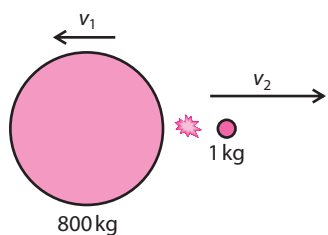


Figure 7.38

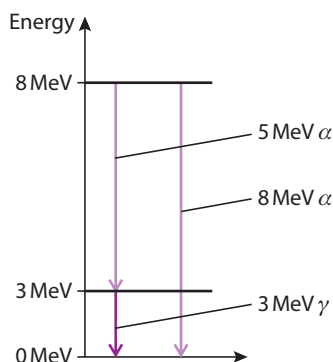
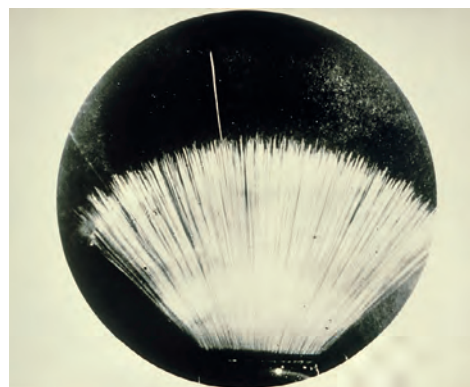


Figure 7.39

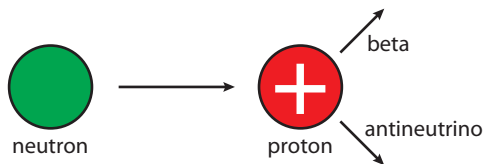


Alpha tracks in a cloud chamber. Note they are all the same length except for one.

Properties of alpha radiation	
Range in air	~5 cm
Penetration	stopped by paper
Ionizing ability	very high
Detection	GM tube, cloud chamber, photographic paper

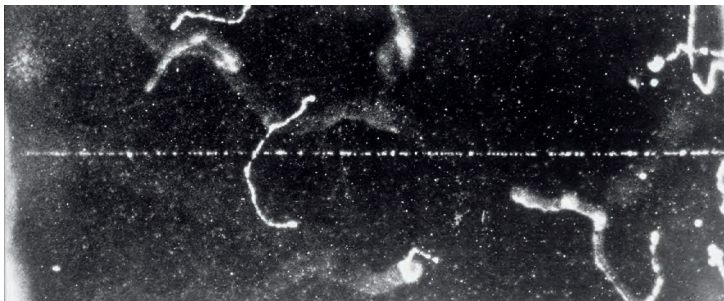
Beta minus (β^-)

Beta minus particles are electrons. They are exactly the same as the electrons outside the nucleus but they are formed when a neutron changes to a proton. When this happens an antineutrino is also produced.



It appears that a neutron must be made of a proton with an electron stuck to it, but this isn't the case. Electrons cannot exist within the nucleus. One reason is that electrons are not affected by the strong force that holds the nucleons together, and the electric attraction between proton and electron is not strong enough to hold the electrons in place. During beta decay, the neutron changes into the proton and electron, rather like the frog that changes to a prince in the fairy tale.

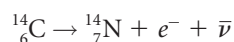
Beta particles are not as heavy as alphas and although they travel with high speed they are not as effective at knocking electrons off atoms. As a result they are not as ionizing, although they do produce enough ions to be detected by a GM tube, cloud chamber or photographic plate. Since betas are not as reactive or ionizing as alphas, they pass through more matter and have a longer range in air.



Properties of beta radiation	
Range in air	~30 cm
Penetration	~1 mm aluminium
Ionizing ability	not very
Detection	GM tube, cloud chamber, photographic paper

Effect on nucleus

When a nucleus emits a beta particle, it loses 1 neutron and gains 1 proton. Carbon-14 decays into nitrogen-14 when it emits a beta particle.



Beta energy

As with alpha decay, the amount of energy available to the beta particles can be calculated from the change of mass that occurs. However, in this case, the energy is shared between the beta and the neutrino. If we measure the KE of the beta particles, we find that they have a range of values, as shown in the beta energy spectrum in Figure 7.41. When beta particles were first discovered, the existence

Figure 7.40 Beta minus decay.

A cloud chamber image of a beta track – notice it is much thinner than the alpha tracks.

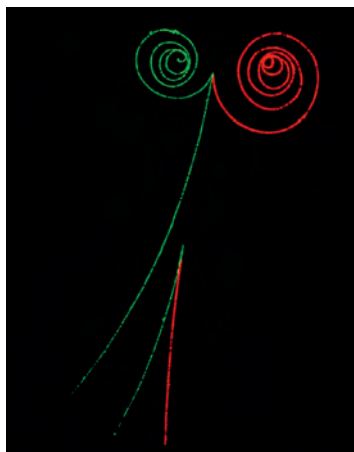
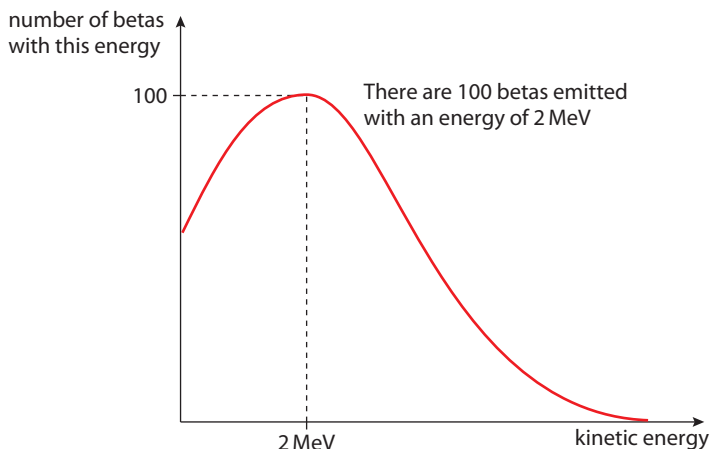


Antineutrino

An antineutrino is the antiparticle of a neutrino. All particles have antiparticles. You will understand more about antiparticles if you do the particle physics option.

of the neutrino was unknown, so physicists were puzzled as to how the beta could have a range of energies; it just isn't possible if only one particle is ejected from a heavy nucleus. To solve this problem, Wolfgang Pauli suggested that there must be an 'invisible' particle coming out too. The particle was called a *neutrino* (small neutral one) since it had no charge and negligible mass. Neutrinos are not totally undetectable and were eventually discovered some 26 years later. However, they are very unreactive; they can pass through thousands of kilometres of lead without an interaction.

Figure 7.41 This graph shows the spread of beta energy. It isn't really a line graph but a bar chart with thin bars. Notice how many betas have zero KE – this is because they are slowed down by electrostatic attraction to the nucleus.



Electrons (green) and positrons (red) are formed from gamma photons. Notice how the B field (into page) causes them to curve in opposite directions. The bottom pair has more KE than the top pair, so the radius of their path is greater.

The mass of a neutron is greater than the mass of a proton, so it is possible for a neutron to change to a proton outside the nucleus. β^+ decay is, however, only possible in a nucleus.

Beta-plus (β^+) decay

A beta-plus is a positive electron, or positron. They are emitted from the nucleus when a proton changes to a neutron. When this happens, a neutrino is also produced.

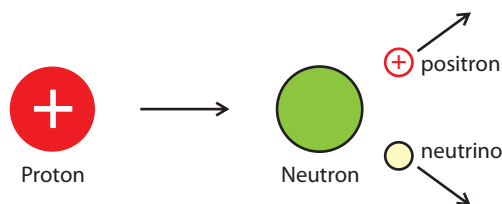
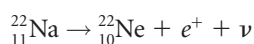


Figure 7.42 Beta-plus decay.

A positron has the same properties as an electron but it is positive (it is the antiparticle of an electron), so beta-plus particles have very similar properties to beta-minus. They penetrate paper, have a range of about 30 centimetres in air, and are weakly ionizing. The beta-plus track in a cloud chamber also looks the same as beta-minus, unless a magnetic field is added. The different charged paths then curve in opposite directions as shown in the photo.

Effect on nucleus

When a nucleus emits a β^+ it loses one proton and gains a neutron. An example of a β^+ decay is the decay of sodium into neon.



Exercises

- 20 $^{45}_{20}\text{Ca}$ (calcium) decays into Sc (scandium) by emitting a β -particle. How many protons and neutrons does Sc have?
- 21 Cs (caesium) decays into $^{137}_{56}\text{Ba}$ (barium) by emitting a β -particle. How many protons and neutrons does Cs have?

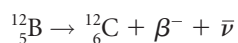
Gamma radiation (γ)

Gamma radiation is electromagnetic radiation, so when it is emitted there is no change in the particles of the nucleus – they just lose energy. Each time a nucleus decays, a photon is emitted. As we have seen, the energy released from nuclear reactions is very high, so the energy of each gamma photon is also high. The frequency of a photon is related to its energy by the formula $E = hf$. This means that the frequency of gamma photons is very high. Their high energy also means that if they are absorbed by atomic electrons, they give the electrons enough energy to leave the atom. In other words they are ionizing – which means they can be detected with a GM tube, photographic paper or a cloud chamber. As they pass easily through human tissue, gamma rays have many medical applications.

Gamma energy

Gamma photons are often emitted when a nucleus is left in an excited state after emitting another form of radiation e.g. beta.

Consider the following example of beta decay



The BE of ^{12}B is 79 MeV and the BE of ^{12}C is 92 MeV

The energy released during this decay is therefore:

$$92 - 79 = 13 \text{ MeV}$$

This can result in a maximum β energy of 13 MeV.

Alternatively, only 10 MeV could be given to the β leaving the nucleus in an excited state. The extra energy could then be released as a gamma photon of energy 3 MeV.

Decay chains

Radioactive nuclei often decay into other nuclei that are also radioactive; these in turn decay, forming what is known as a *decay chain*. An example of a decay chain is the uranium-235 series that starts with plutonium and ends with lead. The table below includes the isotopes at the start of this series.

Table of nuclear masses			
Z	Symbol	A	Mass (u)
94	Pu	239	239.052156
92	U	235	235.043923
91	Pa	231	231.035883
90	Th	231	231.036304
90	Th	227	227.027704
89	Ac	227	227.027752



Antimatter

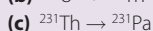
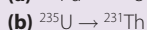
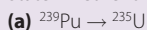
It is also possible for a proton to change into a neutron and a positive electron plus a neutrino. The positron is in some way the opposite of an electron – it is called an *antiparticle*. The antineutrino $\bar{\nu}$ is also the antiparticle of the neutrino. Every particle has an antiparticle. Atoms made of negative positrons and positive electrons are called *antimatter*.

Note:

For the alpha decays in the following exercises, you will also need to know that the mass of an alpha particle is 4.002602 u. But you don't need to include the mass of the beta since it is already taken into account. This is because the masses are actually atomic masses, which include the electrons in a neutral atom. If you add up the electrons, you will discover that there is already an extra one on the left of the equation.

Exercises

22 State whether the following are α - or β -decays.



23 In each of the examples above, use the information in the table to calculate the energy released.

Nuclear radiation and health

Alpha and beta particles have energies measured in MeV. To ionize an atom requires about 10 eV, so each particle can ionize 10^5 atoms before they have run out of energy. When radiation ionizes atoms that are part of a living cell, it can affect the ability of the cell to carry out its function or even cause the cell wall to be ruptured. If a large number of cells that are part of a vital organ are affected then this can lead to death. In minor cases the effect is similar to a burn. The amount of harm that radiation can cause is dependent on the number and energy of the particles. When a gamma photon is absorbed, the whole photon is absorbed so one photon can ionize only one atom. However, the emitted electron has so much energy that it can ionize further atoms, leading to damage similar to that caused by alpha and beta.

Very high dose

- Can affect the central nervous system, leading to loss of coordination and death within two or three days.

Medium dose

- Can damage the stomach and intestine, resulting in sickness and diarrhoea and possibly death within weeks.

Low dose

- Loss of hair, bleeding and diarrhoea.

Safe dose

- All ionizing radiation is potentially harmful so there is no point below which it becomes totally safe. However, at very low levels the risk is small and can be outweighed by the benefits gained when, for example, an X-ray is taken of a broken leg.

Long term

- There is some evidence that after exposure to radiation, the probability of getting cancer or having a child with a genetic mutation increases.

Cancer

Rapidly dividing cancer cells are very susceptible to the effects of radiation and are more easily killed than normal cells. In radiotherapy, nuclear radiation is used to cure cancer by killing the cancerous cells.



A radiation burn caused during radiotherapy for cancer.

A lot of the data about the effect of radiation comes from studying the victims of the atom bombs dropped on Japan in the Second World War. Is it ethically correct to use this data?



Protection against radiation

There are two ways that we can reduce the effect of nuclear radiation: distance and shielding. Alpha and beta radiation have a very short range in air, so will not be dangerous a few metres from the source. The number of gamma photons decreases proportional to $\frac{1}{r^2}$ (where r is the distance from the source), so the further away you are, the safer you will be. Although alpha is the most ionizing radiation, it can be stopped by a sheet of paper (although this means that alpha is the most harmful if ingested). Beta and gamma are more penetrating, so need a thick lead shield to provide protection.

7.7 Half-life

Assessment statements

- 7.2.6 State that radioactive decay is a random and spontaneous process and that the rate of decay decreases exponentially with time.
- 7.2.7 Define the term *radioactive half-life*.
- 7.2.8 Determine the half-life of a nuclide from a decay curve.
- 7.2.9 Solve radioactive decay problems involving integral numbers of half-lives.
- 13.2.5 State the radioactive decay law as an exponential function and define the decay constant.
- 13.2.6 Derive the relationship between decay constant and half-life.
- 13.2.7 Outline methods for measuring the half-life of an isotope.
- 13.2.8 Solve problems involving radioactive half-life.

A nucleus that can decay into another is said to be unstable; the more energy released, the more unstable the nucleus is.

It is not possible to say exactly when an unstable nucleus will decay, but if you compare two nuclei, then the one that is most unstable is most likely to decay first. It is like watching two leaves on a tree – you don't know which will fall first, but the brown crinkly one will probably fall before the green one. Staying with the tree analogy, it is also the case that the number of leaves that fall in an hour will be greater if there are more leaves on the tree. In the same way, the number of decays per unit time of an amount of unstable material is proportional to the number of nuclei.

$$\text{Rate of decay} \propto \text{number of nuclei.}$$

The exponential decay curve

If we start with 100 unstable nuclei, then as time progresses and the nuclei decay, the number of nuclei remaining decreases. As this happens, the rate of decay also decreases. If we plot a graph of the number of nuclei against time, the gradient (rate of decay) starts steep but gets less steep with time.

This curve tends towards zero but will never get there (it's an asymptote), so it is impossible to say at what time the last nucleus will decay. However, we can say how long it will take for *half* of the nuclei to decay – this is called the *half-life*.



A suit designed to protect the wearer from radiation.



To view a simulation of random decay, visit www.heinemann.co.uk/hotlinks, enter the express code 4426P and click on Weblink 7.4.

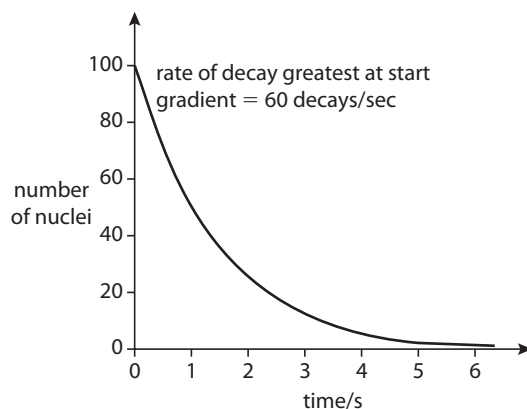
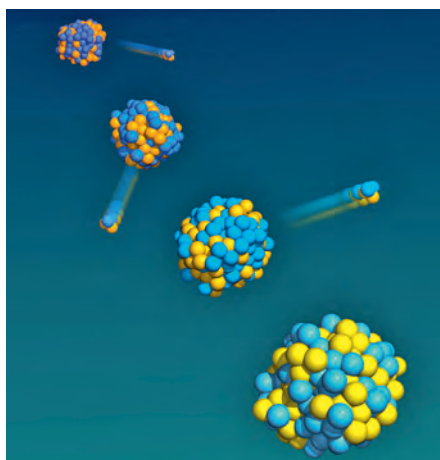


Figure 7.43 The shape of the decay curve is an exponential.

An artist's impression of nuclei randomly emitting alpha particles.

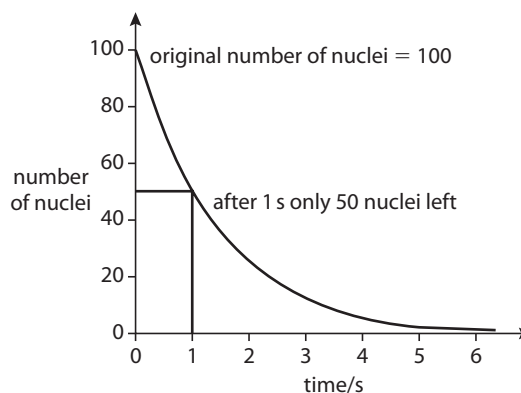


Half-life

The half-life is defined as the time taken for half of the nuclei in a sample to decay.

In Figure 7.44, you can see that the time taken for the original 100 nuclei to decay to 50 is 1 second. The half-life of this material is therefore 1 second. You can also see that after each further second the number of nuclei keeps on halving.

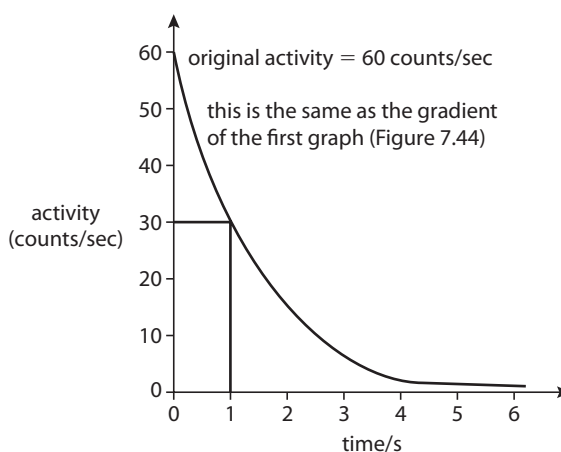
Figure 7.44 Decay curve showing half-life.



Activity

It is not very easy to count the number of undecayed nuclei in a sample – it is much easier to measure the radiation. Since the rate of decay is proportional to the number of nuclei, a graph of the rate of particle emission against time will have the same shape.

Figure 7.45 Activity vs time.



Worked examples

Cobalt-60 decays by beta emission and has a half-life of approximately 5 years. If a sample of cobalt-60 emits 40 beta particles per second, how many will the same sample be emitting in 15 years time?

Solution

After 5 years the activity will be 20 particles per second.

After another 5 years it will be 10 particles per second.

Finally after a further 5 years it will emit 5 particles per second (5 Bq).

Exercises

- 24 ^{17}N decays into ^{17}O with a half-life of 4 s. How much ^{17}N will remain after 16 s, if you start with 200 g?
- 25 ^{11}Be decays into ^{11}B with a half-life of 14 s. If the ^{11}Be emits 100 particles per second, how many particles will it emit after 42 s?
- 26 A sample of dead wood contains $\frac{1}{16}$ of the amount of ^{14}C that it contained when alive. If the half-life of ^{14}C is 6000 years how old is the sample?

The exponential decay equation

If the time for a decay is a whole number of half-lives, it is easy to calculate how much of a sample has decayed. However, if not then you need to use the decay equation.

We have seen that radioactive decay is a random process, therefore: the rate of decay is proportional to the number of undecayed nuclei. We can write this a differential equation:

$$\frac{dN}{dt} = -\lambda N$$

where λ is the decay constant.

You have probably learnt how to solve equations like this in mathematics, using the method of 'separation of variables' and integrating between time 0 when $N = N_0$ and time t when $N = N_t$.

The solution is:

$$N_t = N_0 e^{-\lambda t}$$

This is called an *exponential decay equation*.

The decay constant

The decay constant, λ tells us how quickly the material will decay. This is illustrated by the two lines in Figure 7.46.

The blue line has the bigger decay constant so decays more rapidly.

From the equation $\frac{dN}{dt} = -\lambda N$ we can see that the units of λ are s^{-1} .

If we only have one nucleus then $\frac{dN}{dt} = -\lambda$. If this is large then the rate of decay of that nucleus is high. But with one nucleus you can't really talk about the rate of decay – instead we really mean the *probability* of it decaying, so λ is the probability of a nucleus decaying in a second.



Becquerel (Bq)

The becquerel is the unit of activity, measured as counts per second.



Carbon dating

There are two isotopes of carbon in the atmosphere: ^{14}C and ^{12}C . ^{12}C is stable but ^{14}C is radioactive with a half-life of 6000 years. However, it is made as quickly as it decays, so the ratio of ^{14}C to ^{12}C is always the same. As plants grow, they continuously absorb carbon from the atmosphere, so the ratio of ^{14}C to ^{12}C is also constant in them. When plants die, the ^{14}C decays, so by measuring the ratio of ^{14}C to ^{12}C , the age of a piece of dead organic matter can be found.



Use of spreadsheets

You can use a spreadsheet like Excel to plot the decay curve and see what happens when you change λ . The exponential equation in Excel is `exp()`.

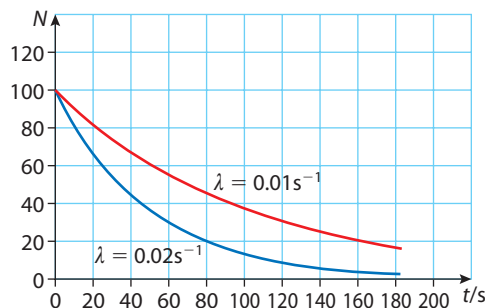


Figure 7.46 Two exponential decays with different decay constants.

Relationship between λ and half-life

The half-life, $t_{\frac{1}{2}}$ is the time taken for the number of nuclei to decay to half the original value. So if the original number of nuclei = N_0 then after $t_{\frac{1}{2}}$ seconds there will be $\frac{N_0}{2}$ nuclei. If we substitute these values into the exponential decay equation, we get:

$$\frac{N_0}{2} = N_0 e^{-\lambda t_{\frac{1}{2}}}$$

Cancelling N_0

$$\frac{1}{2} = e^{-\lambda t_{\frac{1}{2}}}$$

Taking natural logs of both sides gives

$$\ln\left(\frac{1}{2}\right) = -\lambda t_{\frac{1}{2}}$$

This is the same as

$$\ln 2 = \lambda t_{\frac{1}{2}}$$

So

$$t_{\frac{1}{2}} = \frac{0.693}{\lambda}$$

So if we know the decay constant, we can find the half-life or vice versa.

Activity equation

The activity, A , of a sample is the number of particles (α , β or γ) emitted per unit time. This is the same as the number of decays per unit time $\left(\frac{dN}{dt}\right)$ so the equation for how the activity varies with time is also exponential.

$$A_t = A_0 e^{-\lambda t}$$

You can use 'decays per second' as the unit of activity, but the SI unit is the becquerel (Bq). This is the amount of a given material that emits 1 particle per second, so if you have a piece of material that has an activity of 5 Bq then it will emit 5 particles per second.

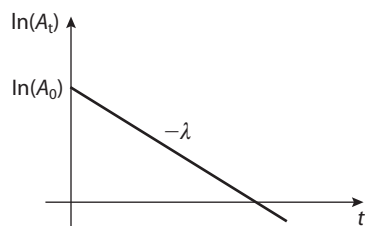


Figure 7.47 Graph used to determine the half-life.

Measuring half-life

There are two ways to measure the half-life of an isotope; either measure the activity over a period of time or the change in number of nuclei.

In the school laboratory you might do an experiment using an isotope with a half-life of a few minutes, such as protactinium. In this case it is possible to measure the count rate every 10 seconds for a couple of minutes and find the half-life from that. The best way to analyse the data is to plot $\ln(A_t)$ against t . If you take logs of the activity equation you get:

$$\ln(A_t) = \ln(A_0) - \lambda t$$

So if you plot $\ln(A_t)$ against t you will get a straight line with $-\lambda$ as the gradient.

If the half-life is very long then you would have to wait a very long time before the count rate changed. In this case, a mass spectrometer could be used to find the number of different nuclei present at different times rather than the activity.

Radioactive dating

Potassium-argon dating

Potassium-argon dating is used to date rocks. Potassium-40 decays to argon-40 with a half-life of 1.26×10^9 years. When rock containing potassium is molten

(hot liquid) any argon that is formed will bubble up to the surface and leave the rock, but when the rock solidifies the argon is trapped. If a rock sample is heated the argon atoms are released and can be counted with a mass spectrometer. If you also count the potassium nuclei you can calculate the age of the rock.

Carbon dating

Carbon dating is only used for organic material up to about 60 000 years old. There are two isotopes of carbon present in living material: carbon-12 and carbon-14. The percentage of $^{14}\text{C}/^{12}\text{C}$ is always the same in living things (about $10^{-10}\%$) but when they die, the ^{14}C begins to decay. As it decays, the percentage decreases exponentially. If you measure the percent of $^{14}\text{C}/^{12}\text{C}$ in a dead specimen, you can calculate its age using the formula

$$\%_{\text{now}} = \%_{\text{originally}} \times e^{-\lambda t}$$

where the original percentage is $10^{-10}\%$.

Worked example

Protactinium has a half-life of 70 s. A sample has an activity of 30 Bq. Calculate its activity after 10 minutes.

Solution

We are going to use the equation $A_t = A_0 e^{-\lambda t}$. First we need to find the decay

$$\text{constant } \lambda = \frac{0.693}{t_{\frac{1}{2}}} = 9.9 \times 10^{-3} \text{ s}^{-1}$$

$$\text{The activity after 700 s is now} = 30 \times e^{-9.9 \times 10^{-3} \times 700} = 0.03 \text{ Bq}$$

Exercises

- 27** A sample has activity 40 Bq. If it has a half-life of 5 mins, what will its activity be after 12 mins?
- 28** The activity of a sample of strontium-90 decreases from 20 Bq to 15.7 Bq in 10 years. What is the half-life of strontium 90?
- 29** A sample of rock is found to contain 7×10^{10} potassium-40 nuclei and 3×10^{10} argon nuclei. Calculate
- the original number of potassium nuclei present in the sample
 - the age of the sample.
- 30** A sample of dead wood contains $0.9 \times 10^{-10}\%$ ^{14}C compared to ^{12}C . What is the age of the sample?
- 31** Cobalt-60 has a half-life of 5.27 years. Calculate
- the half-life in s
 - the decay constant in s^{-1}
 - the number of atoms in one gram of ^{60}Co
 - the activity of 1 gram of ^{60}Co
 - the amount of ^{60}Co in a sample with an activity of 50 Bq.



Radioactive dating brings science into conflict with some religions, as the age of Earth calculated from radioactive dating doesn't agree with the age given in religious teaching. How can these conflicts be resolved?



^{14}C half-life

The half-life of ^{14}C is 6000 years. It can't be used to date samples older than about 10 half-lives (60 000 years).

● **Hint:** You don't have to convert everything into seconds. If half-life is in years then λ is year^{-1} .

7.8 Nuclear reactions

Assessment statements

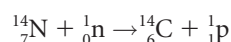
- 7.3.1 Describe and give an example of an artificial (induced) transmutation.
- 7.3.2 Construct and complete nuclear equations.
- 7.3.8 Describe the processes of nuclear fission and nuclear fusion.
- 7.3.9 Apply the graph in 7.3.6 to account for the energy release in the processes of fission and fusion.
- 7.3.10 State that nuclear fusion is the main source of the Sun's energy.
- 7.3.11 Solve problems involving fission and fusion reactions.

Transmutation

We have seen how nuclei can change from one form to another by emitting radioactive particles. It is also possible to change a nucleus by adding nucleons. These changes or transmutations can occur naturally, as in the production of nitrogen from carbon in the atmosphere, or can be artificially initiated by bombarding a target material with high-energy particles.

Transmutation of nitrogen into carbon

Nuclide/particle	Mass (u)
^{14}N	14.0031
neutron	1.008664
^{14}C	14.003241
proton	1.007825



In this reaction, a nitrogen nucleus absorbs a neutron and gives out a proton.

Note: In all nuclear reactions, the nucleon number and proton number must balance.

Comparing the masses before and after the reaction:

$$\text{Initial mass} - \text{final mass} = 0.000698 \text{ u}$$

This loss of mass must have been converted to the KE of the proton.

$$E = 931.5 \times 0.000698 = 0.65 \text{ MeV}$$

Remember: $1 \text{ u} = 931.5 \text{ MeV}$.

Exercises

32 In the following transmutations, fill in the missing nucleon and proton numbers.

- (a) ${}^4_2\text{He} + {}^{16}_8\text{O} \rightarrow {}^?_9\text{F} + {}^1_? \text{H} + {}^1_0\text{n}$
- (b) ${}^4_2\text{He} + {}^{121}_{51}\text{Sb} \rightarrow {}^?_? \text{I} + 2{}^1_0\text{n}$
- (c) ${}^2_1\text{H} + {}^{17}_7\text{N} \rightarrow {}^?_8\text{O} + {}^1_0\text{n}$
- (d) ${}^{31}_{15}\text{P} \rightarrow {}^?_{15}\text{P} + {}^1_0\text{n} + \gamma$

33 (a) Using the table, calculate the change in mass in Question 32 (a).

Nuclide/particle	Mass (u)
${}^4\text{He}$	4.002 603
${}^{16}\text{O}$	15.994 914
${}^{18}\text{F}$	18.998 403
${}^1\text{H}$	1.007 825
neutron	1.008 664

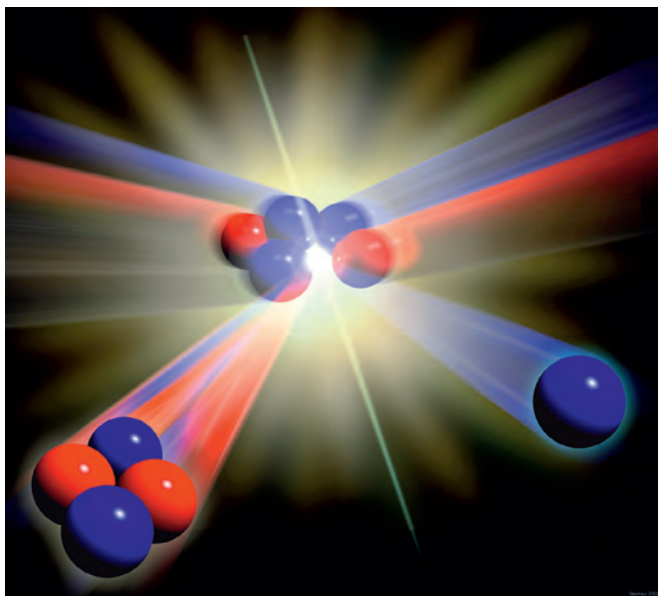
You will notice that this is a negative number, which means that energy is required to make it happen. This energy is supplied by a particle accelerator used to accelerate the helium nucleus.

(b) From your previous answer calculate the KE of the He nucleus.

Nuclear fusion

Nuclear fusion is the joining up of two small nuclei to form one big one.

If we look at the BE/nucleon vs nucleon number curve (Figure 7.48), we see that the line initially rises steeply. If you were to add two ${}^2_1\text{H}$ nuclei to get one ${}^4_2\text{He}$ nucleus, then the He nucleus would have more BE per nucleon.



An artist's impression of the fusion of ${}^2\text{H}$ and ${}^3\text{H}$ to form ${}^4\text{He}$.

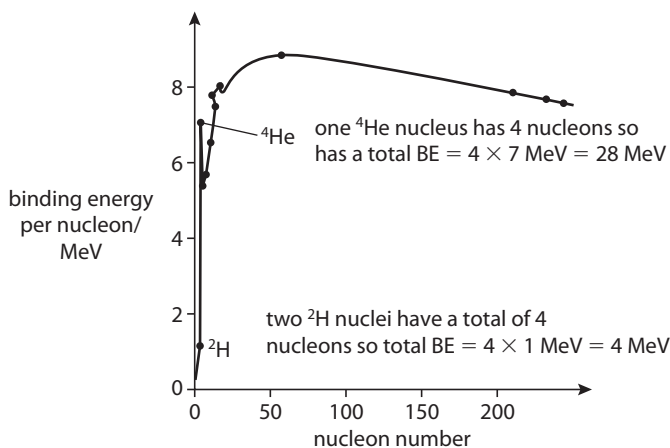


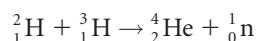
Figure 7.48 BE/nucleon vs nucleon number curve, showing fusion possibility.

If we add up the total BE for the helium nucleus, it has 24 MeV more BE than the two hydrogen nuclei. This means that 24 MeV would have to be released; this could be by the emission of gamma radiation.

Nuclide	Mass in u
^1H	1.007825
^2H	2.014 101
^3H	3.016 049
^3He	3.016 029
^4He	4.002 603
^1_0n	1.008 664

Worked example

Calculate the energy released by the following reaction:



Solution

If the masses are added, we find that the mass of the original nuclei is greater than the mass of the final ones. This mass has been converted to energy.

Mass difference = 0.018883 u

1u is equivalent to 931.5 MeV so energy released = 17.6 MeV

It wouldn't be possible to conserve both KE and momentum if two fast moving nuclei collided and fused together. That's why all the reactions result in two particles not one big one.



Each small nucleus has a positive charge so they will repel each other. To make the nuclei come close enough for the strong force to pull them together, they must be thrown together with very high velocity. For this to take place, the matter must either be heated to temperatures as high as the core of the Sun (about 13 million kelvin) or the particles must be thrown together in a particle accelerator.

The fusion reaction produces a lot of energy per unit mass of fuel and much research has been carried out to build a fusion reactor. You can read more about this in Chapter 8.

Exercises

34 Use the data in the table above to calculate the change in mass and hence the energy released in the following examples of fusion reactions:

- (a) $^2_1\text{H} + ^2_1\text{H} \rightarrow ^3_2\text{He} + ^1_0\text{n}$
- (b) $^2_1\text{H} + ^2_1\text{H} \rightarrow ^3_1\text{H} + ^1_1\text{p}$
- (c) $^2_1\text{H} + ^3_2\text{He} \rightarrow ^4_2\text{He} + ^1_1\text{p}$

Nuclear fission

Looking at the right-hand side of the graph we see that if one large nucleus is split into two smaller ones, then the total BE would again be increased. This reaction forms the basis of the nuclear reactor that you will learn more about in Chapter 8.

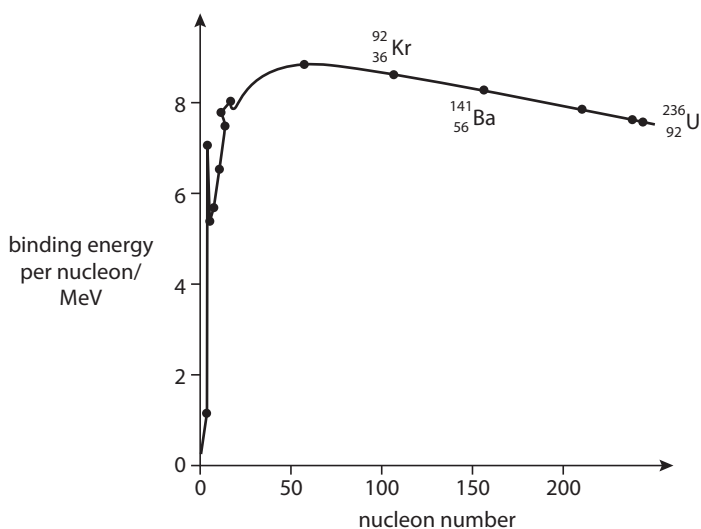


Figure 7.49 BE/nucleon vs nucleon number curve showing fission possibility.

Worked example

Find the energy released if uranium-236 splits into krypton-92 and barium-141.

Solution

$$\text{BE of } ^{236}\text{U} = 236 \times 7.6$$

$$= 1793.6 \text{ MeV}$$

$$\text{BE of } ^{141}\text{Ba} = 141 \times 8$$

$$= 1128 \text{ MeV}$$

$$\text{BE of } ^{92}\text{Kr} = 92 \times 8.2$$

$$= 754.4 \text{ MeV}$$

$$\text{Gain in BE} = (1128 + 754.4) - 1793.6$$

$$= 88.8 \text{ MeV}$$

Since this leads to a release of energy, this process is possible.

● **Examiner's hint:** Use the graph to find the BE per nucleon.

Exercises

Table of nuclear masses			
Z	Symbol	A	Mass (u)
92	U	233	233.039628
92	U	236	236.045563
42	Mo	100	99.907476
50	Sn	126	125.907653
56	Ba	138	137.905233
36	Kr	86	85.910615
0	n	1	1.008664

Use the table above to answer the following questions.

35 If ^{236}U splits into ^{100}Mo and ^{126}Sn , how many neutrons will be produced? Calculate the energy released in this reaction.

36 ^{233}U splits into ^{138}Ba and ^{86}Kr plus 9 neutrons. Calculate the energy released when this takes place.

● **Examiner's hint:** To answer these questions you must find the difference in mass between the original nucleus and the products. To convert to MeV, simply multiply by 931.5.

Practice questions

1 This question is about nuclear reactions.

- (a) Complete the table below, by placing a tick (✓) in the relevant columns, to show how an increase in each of the following properties affects the rate of decay of a sample of radioactive material.

Property	Effect on rate of decay		
	increase	decrease	stays the same
temperature of sample			
pressure on sample			
amount of sample			

(2)

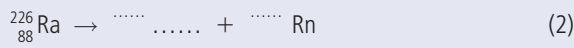
Radium-226 ($^{226}_{88}\text{Ra}$) undergoes natural radioactive decay to disintegrate spontaneously with the emission of an alpha particle (α -particle) to form radon (Rn). The masses of the particles involved in the reaction are

radium: 226.0254 u

radon: 222.0176 u

α -particle: 4.0026 u

- (b) (i) Complete the nuclear reaction equation below for this reaction.



- (ii) Calculate the energy released in the reaction. (3)

- (c) The radium nucleus was stationary before the reaction.

- (i) Explain, in terms of the momentum of the particles, why the radon nucleus and the α -particle move off in opposite directions after the reaction. (3)

- (ii) The speed of the radon nucleus after the reaction is v_{R} and that of the α -particle is v_{α} . Show that the ratio $\frac{v_{\alpha}}{v_{\text{R}}}$ is equal to 55.5. (3)

- (iii) Using the ratio given in (ii) above, deduce that the kinetic energy of the radon nucleus is much less than the kinetic energy of the α -particle. (3)

- (d) Not all of the energy of the reaction is released as kinetic energy of the α -particle and of the radon nucleus. Suggest **one** other form in which the energy is released. (1)

Another type of nuclear reaction is a fusion reaction. This reaction is the main source of the Sun's radiant energy.

- (e) (i) State what is meant by a *fusion reaction*.

- (ii) Explain why the temperature and pressure of the gases in the Sun's core must both be very high for it to produce its radiant energy. (5)

(Total 25 marks)

2 This question is about nuclear reactions.

- (a) (i) Distinguish between *fission* and *radioactive decay*. (4)

A nucleus of uranium-235 ($^{235}_{92}\text{U}$) may absorb a neutron and then undergo fission to produce nuclei of strontium-90 ($^{90}_{38}\text{Sr}$) and xenon-142 ($^{142}_{54}\text{Xe}$) and some neutrons.

The strontium-90 and the xenon-142 nuclei both undergo radioactive decay with the emission of β^{-} particles.

- (ii) Write down the nuclear equation for this fission reaction. (2)

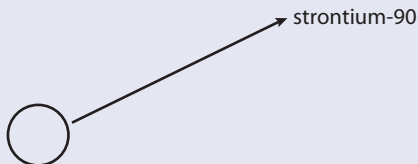
- (iii) State the effect, if any, on the mass number (nucleon number) and on the atomic number (proton number) of a nucleus when the nucleus undergoes β^{-} decay.

Mass number: Atomic number: (2)

The uranium-235 nucleus is stationary at the time that the fission reaction occurs. In this fission reaction, 198 MeV of energy is released. Of this total energy, 102 MeV and 65 MeV are the kinetic energies of the strontium-90 and xenon-142 nuclei respectively.

- (b) (i)** Calculate the magnitude of the momentum of the strontium-90 nucleus. (4)
(ii) Explain why the magnitude of the momentum of the strontium-90 nucleus is not exactly equal in magnitude to that of the xenon-142 nucleus. (2)

On the diagram right, the circle represents the position of a uranium-235 nucleus before fission. The momentum of the strontium-90 nucleus after fission is represented by the arrow.



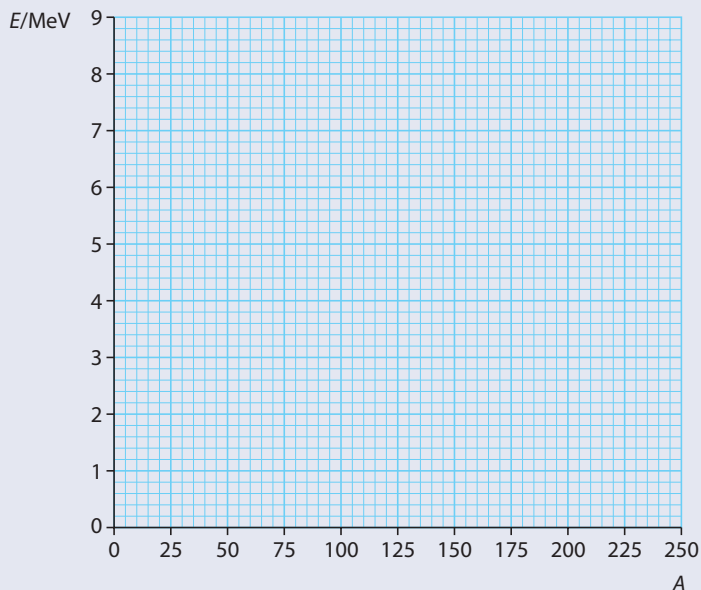
- (iii)** On the diagram above, draw an arrow to represent the momentum of the xenon-142 nucleus after the fission. (2)
- (c)** In a fission reactor for the generation of electrical energy, 25% of the total energy released in a fission reaction is converted into electrical energy.
- (i)** Using the data in **(b)**, calculate the electrical energy, in joules, produced as a result of nuclear fission of one nucleus. (2)
- (ii)** The specific heat capacity of water is $4.2 \times 10^3 \text{ J kg}^{-1}$. Calculate the energy required to raise the temperature of 250 g of water from 20°C to its boiling point (100°C). (3)
- (iii)** Using your answer to **(c)(i)**, determine the mass of uranium-235 that must be fissioned in order to supply the amount of energy calculated in **(c)(ii)**. The mass of a uranium-235 atom is $3.9 \times 10^{-25} \text{ kg}$. (4)

(Total 25 marks)

3 This question is about nuclear binding energy.

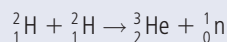
- (a) (i)** Define *nucleon*. (1)
(ii) Define *nuclear binding energy of a nucleus*. (1)

The axes below show values of nucleon number A (horizontal axis) and average binding energy per nucleon E (vertical axis). (Binding energy is taken to be a positive quantity.)



- (b) Mark on the E axis above, the approximate position of
- (i) the isotope $^{56}_{26}\text{Fe}$ (label this F). (1)
 - (ii) the isotope ^2_1H (label this H). (1)
 - (iii) the isotope $^{238}_{92}\text{U}$ (label this U). (1)
- (c) Using the grid in part (a), draw a graph to show the variation with nucleon number A of the average binding energy per nucleon E . (2)
- (d) Use the following data to deduce that the binding energy per nucleon of the isotope ^3_2He is 2.2 MeV.
- | | | | |
|---------------------------------|---|-----------|-----|
| nuclear mass of ^3_2He | = | 3.01603 u | |
| mass of proton | = | 1.00728 u | |
| mass of neutron | = | 1.00867 u | (3) |

In the nuclear reaction



energy is released.

- (e) (i) State the name of this type of reaction. (1)
- (ii) Use your graph in (c) to explain why energy is released in this reaction. (2)
- (Total 13 marks)

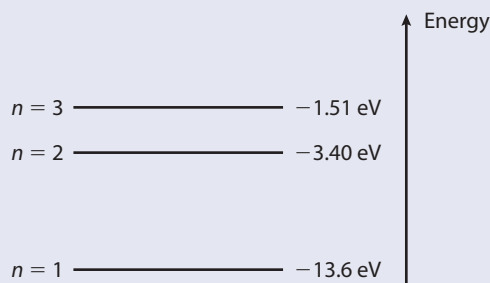
4 This question is about the wave nature of matter.

- (a) Describe the concept of matter waves and state the de Broglie hypothesis (3)
- (b) An electron is accelerated from rest through a potential difference of 850 V. For this electron
- (i) calculate the gain in kinetic energy. (1)
 - (ii) deduce that the final momentum is 1.6×10^{-23} Ns. (2)
 - (iii) determine the associated de Broglie wavelength. (2)
- (Electron charge $e = 1.6 \times 10^{-19}$ C, Planck constant $h = 6.6 \times 10^{-34}$ J s)
- (Total 8 marks)

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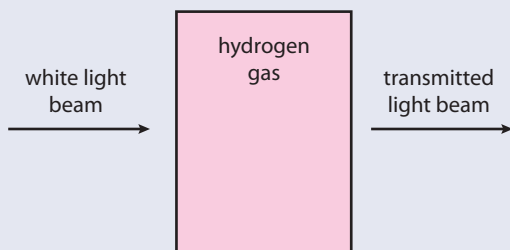
5 This question is about the Bohr model of the hydrogen atom.

- (a) The diagram below shows the three lowest energy levels of a hydrogen atom as predicted by the Bohr model.



State **two** physical processes by which an electron in the ground state energy level can move to a higher energy level state. (2)

- (b) A parallel beam of white light is directed through monatomic hydrogen gas as shown in the diagram opposite. The transmitted light is analysed.



White light consists of photons that range in wavelength from approximately 400 nm for violet to 700 nm for red light.

- (i) Determine that the energy of photons of light of wavelength 658 nm is about 1.89 eV. (2)
- (ii) The intensity of light of wavelength 658 nm in the direction of the transmitted beam is greatly reduced. Using the energy level diagram in (a) explain this observation. (3)
- (iii) State **two** ways in which the Schrödinger model of the hydrogen atom differs from that of the Bohr model. (2)

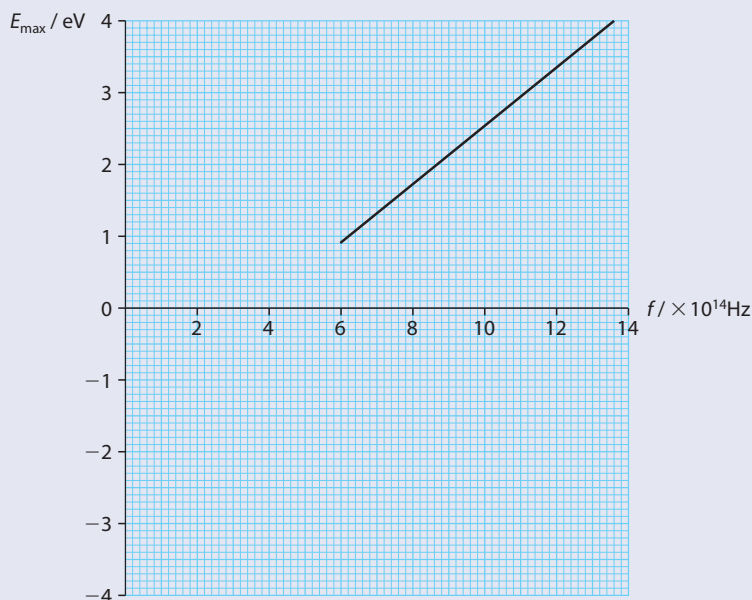
(Total 9 marks)

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6 This question is about the photoelectric effect.

- (a) State **one** aspect of the photoelectric effect that **cannot** be explained by the wave model of light. Describe how the photon model provides an explanation for this aspect. (2)

Light is incident on a metal surface in a vacuum. The graph below shows the variation of the maximum kinetic energy E_{\max} of the electrons emitted from the surface with the frequency f of the incident light.



- (b) Use data from the graph to determine
 - (i) the threshold frequency. (2)
 - (ii) a value of the Planck constant. (2)
 - (iii) the work function of the surface. (2)

The threshold frequency of a different surface is 8.0×10^{14} Hz.

- (c) On the axes opposite, draw a line to show the variation with frequency f of the maximum kinetic energy E_{max} of the electrons emitted. (2)

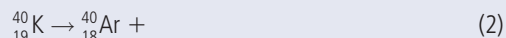
(Total 10 marks)

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7 This question is about radioactive decay and the age of rocks.

A nucleus of the radioactive isotope potassium-40 decays into a stable nucleus of argon-40.

- (a) Complete the equation below for the decay of a potassium-40 nucleus. (2)



A certain sample of rocks contains 1.2×10^{-6} g of potassium-40 and 7.0×10^{-6} g of trapped argon-40 gas.

- (b) Assuming that all the argon originated from the decay of potassium-40 and that none has escaped from the rocks, calculate what mass of potassium was present when the rocks were first formed. (1)

The half-life of potassium-40 is 1.3×10^9 years.

- (c) Determine (2)
 (i) the decay constant of potassium-40. (2)
 (ii) the age of the rocks. (2)

(Total 7 marks)

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8 This question is about charged particles in a magnetic field.

A beam of singly ionized atoms moving at speed v enters a region of magnetic field strength B as shown below.



The magnetic field is directed into the plane of the paper. The ions follow a circular path,

- (a) Deduce that the radius r of the circular path is given by

$$r = \frac{mv}{Bq}$$

where m and q are the mass and charge respectively of the ions. (2)

In one particular experiment, the beam contains singly ionized neon atoms all moving at the same speed. On entering the magnetic field, the beam divides in two. The path of the ions of mass 20 u has radius 15.0 cm.

- (b) Calculate, in terms of u, the mass of the ions having a path of radius 16.5 cm. (2)

The atomic number (proton number) of neon is 10.

- (c) State the number of protons and neutrons in each type of neon ion. (2)

(Total 6 marks)

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