CHAPTER

8 Subatomic particles

REMEMBER

Before beginning this chapter you should be able to:

- recall that all matter is made up of atoms
- explain the arrangement of particles in atoms, in particular that atoms have a central nucleus containing protons and neutrons.

KEY IDEAS

After completing this chapter you should be able to:

- compare and contrast leptons and hadrons, and mesons and baryons
- explain that for every particle that exists there is an antimatter particle of equal mass and opposite charge
- explain that when a particle collides with its antiparticle they annihilate each other, creating radiation
- describe components of sub-atomic particles such as quarks
- relate the discoveries of the neutron, neutrino, positron and Higgs boson to predictions about their existence
- explain how an acceleration of charges produces light, an electromagnetic wave
- describe how an electron radiating energy at a tangent to its circular path produces synchrotron radiation
- describe how electrons moving between energy levels within an atom produce light.

Cosmic rays are thought to originate in supernovae, such as the Crab Nebula, seen here, and the centre of galaxies. When cosmic rays enter the Earth's atmosphere, collisions produce a shower of charged subatomic particles and gamma rays at the Earth's surface.

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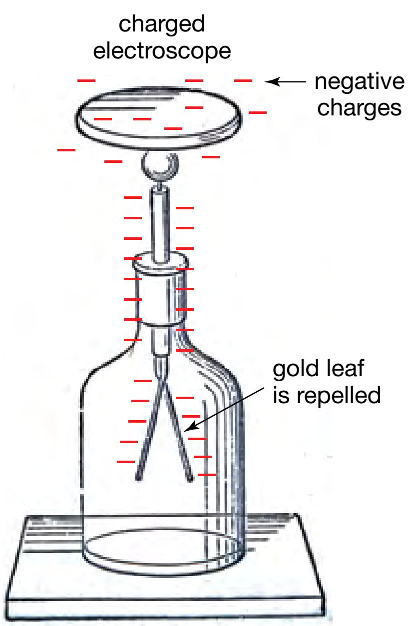
Unit 1 AOS 3 Topic 2 Concept 4

Prediction and discovery
Concept summary and practice questions



Cosmic rays are very energetic charged particles that enter our atmosphere. They are mainly protons and originate from beyond the solar system.

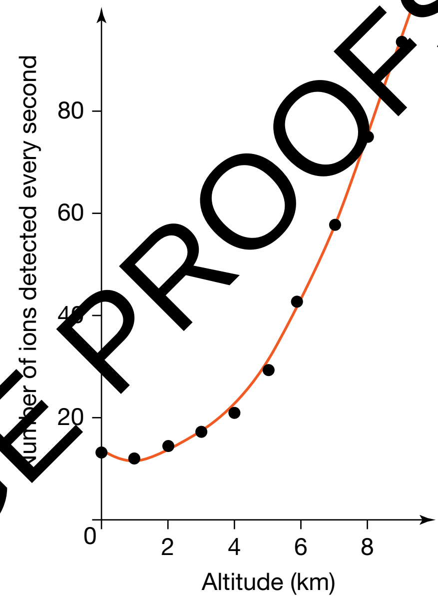
The discovery of subatomic particles

This chapter covers the events of the discovery of subatomic particles from the beginning of the 20th century to the current day. The timeline shown in chapter 7 on pages 100–1 describes many of the steps along the way to what seems now to be a complete understanding of the nature of matter.

Cosmic rays

Natural radioactivity was first discovered when beta particles exposed photographic plates. One of the other technologies used to investigate radioactivity was the gold leaf electroscope. Electroscopes show the presence of electric charge. A charged electroscope slowly loses charge due to the ions in the air produced by radioactive elements in the Earth's crust. It was thought that this effect would decrease with height above the ground.

However, in 1909 it was found that the intensity of radiation was greater on top of the Eiffel Tower. Balloon flights then showed the intensity continued to increase with height, suggesting that the radiation may originate from space. So, the name '**cosmic rays**' was coined.



Number of charged particles from cosmic rays varies by altitude above the Earth's surface

Revision question 8.1

In the graph above, the number of ions detected initially decreases with height, then above 1 km above the Earth's surface it increases quite rapidly. Suggest a reason why there is a strong reading at the Earth's surface that then decreases with height.

Initially cosmic rays were called 'rays' because they were thought to be like light. However, even though they are now known to be particles, the name has stuck. Further investigation over the following decades showed that the particles entering the Earth's atmosphere were mainly protons. The particles seemed to come from beyond the solar system from all points of the sky. Indeed now they are thought to originate in supernovae and the centre of galaxies. They are also extremely fast and energetic. The energy of these protons is 40 million times the energy of the protons in the Large Hadron Collider used to produce the Higgs boson.

When these protons with their massive energy hit an atom in the upper atmosphere, they cause a cascade of successive collisions that produces a shower of charged particles and gamma rays at the Earth's surface.

On average, cosmic rays contribute about 16% of your exposure to ionising radiation from natural sources. This exposure increases the more you fly in a plane and the higher you fly.

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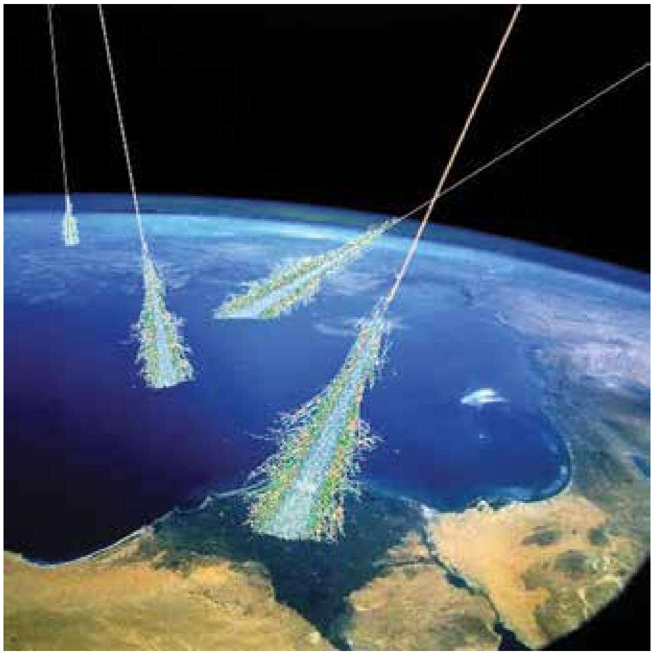
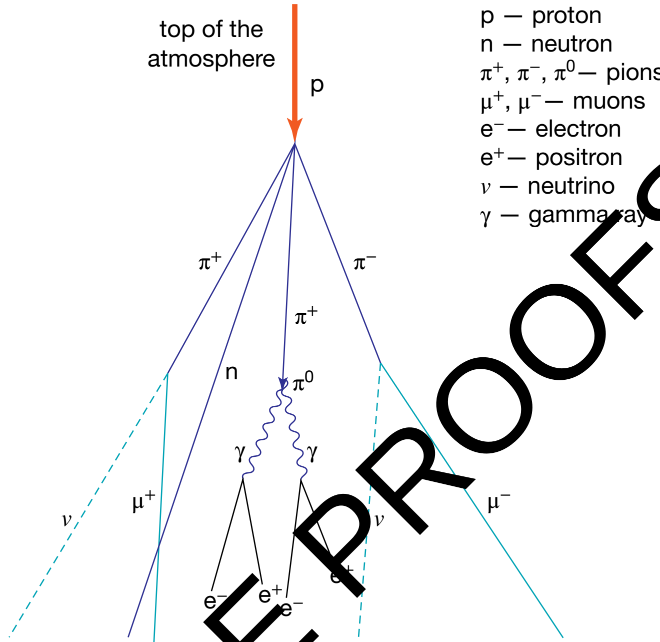


Cosmic ray shower hitting the atmosphere



Revision question 8.2

Cosmic rays are often described as cosmic ray 'showers'. Why is this word an appropriate description?

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Interactivity
Electrons and positrons
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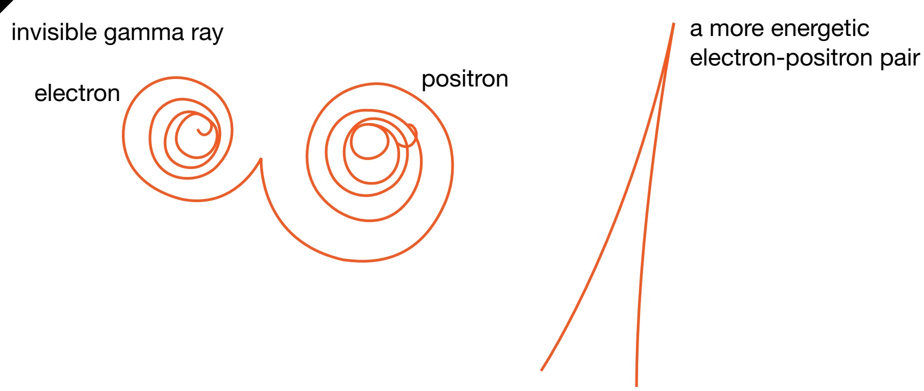
In 1933 Carl Anderson was investigating the charged particles in cosmic ray showers and observed a particle that had the same mass as the electron, but with a positive charge. He had discovered a new particle, the positron.

The chamber Anderson used to detect this charged particle was placed in a strong magnetic field so that a positively charged particle would curve one way and a negatively charged particle would curve the other way. In this experimental set up, an incoming gamma ray collides with a nucleus; the energy of the gamma ray is converted into mass, using $E = mc^2$, but because charge needs to be conserved, two particles of opposite sign are produced.



A gamma ray produces an electron and a positron. The spiralling is due to the slow loss of energy as the track is created.

Revision question 8.3

What aspect of the more energetic pair of tracks do you think indicates that the electron and positron are moving faster?

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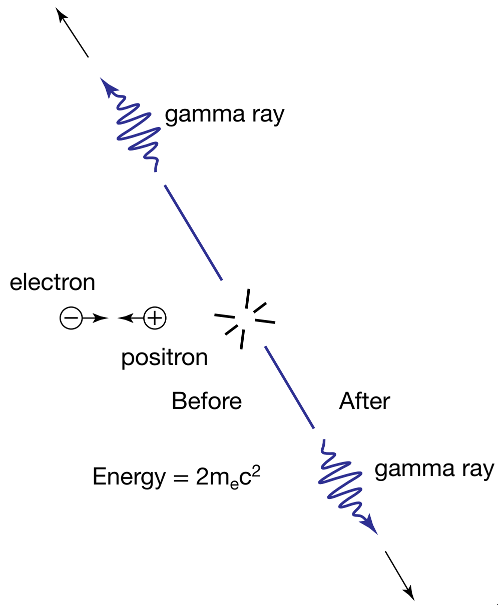

A particle and antiparticle annihilate each other with their mass producing two gamma rays.

The reverse process is also possible. An electron and a positron, or indeed, any particle and its antiparticle, can collide and annihilate each other, producing two gamma rays.

Explaining the strong nuclear force

Also in the 1930s, Hideki Yukawa was seeking an explanation for the properties of the strong nuclear force that exists between particles inside the nucleus. It was known that this force had a very short range, with each proton or neutron attracted only to its near neighbours, not the whole nucleus. Yukawa suggested that a previously unobserved particle acted as 'glue' between pairs of protons in the nucleus, as well as between other pairings. To fit the known features of the strong force, he determined the properties of this unobserved particle. He said it should:

- be about 200 times the mass of the electron
- have the same charge size as the electron
- come in two types: positive and negative
- have a very short half-life of about a millionth of a second
- interact very strongly with nuclei.

In 1936 Carl Anderson's group found such a particle in cosmic ray showers. This particle was named the muon. However, while the muon satisfied the first four points above, it became apparent that its interaction with nuclei was very weak, so the muon was not a good candidate to explain the strong nuclear force.

A few years later, Cecil Powell investigated cosmic ray showers at high altitude in the Pyrenees and the Andes. These observations were higher up in the cascade of collisions that cosmic rays set off when they hit the atmosphere. At this altitude, Powell found another particle that better fit the needs of the strong nuclear force. This particle is called the π-meson or pion.

Shortly after Powell's discovery, the pion was also detected in the laboratory when carbon nuclei were bombarded with high energy alpha particles. After this time, most new particles were found in laboratories using particle accelerators.

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Forces and nuclear stability
Concept summary and practice questions

Revision question 8.4

A possible reaction for the formation of the pion from a carbon nucleus and alpha particle is that the alpha particle and carbon nucleus join with the pion being emitted. Complete the nuclear equation below by determining the values of X and Y, and the symbol for the chemical element, Z. Note the pion has a charge of +1.

$${}^{4}_{2}\text{He} + {}^{12}_{6}\text{C} \rightarrow {}^{x}_{y}\text{Z} + {}^{0}_{1}\pi$$

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So many particles!

In the years that followed, even more particles were discovered, so that now there are over 200 subatomic particles. In the 19th century chemists had to make sense of the large array of chemical elements. The periodic table was the result, with gaps for yet to be found elements. In the late 20th century, physicists needed to find some pattern among the particles.

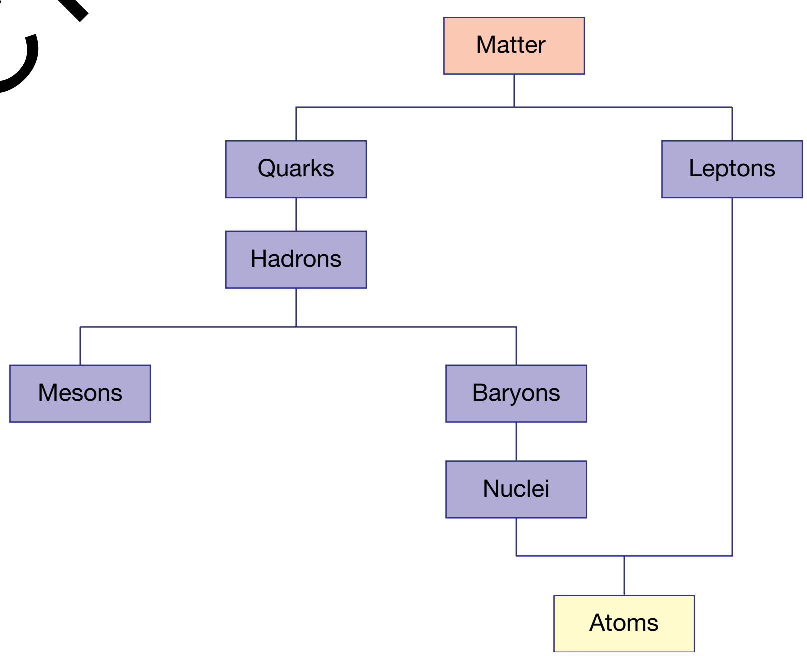
TABLE 8.1 Comparison of the discovery of chemical elements and subatomic particles

Discovery of elements		Discovery of subatomic particles	
Time	**Progress**	**Time**	**Progress**
Late 18th century	About 30 elements known	By 1920	2 known (p and e^-)
Mid 19th century	About 60 elements known; Mendeleev produces periodic table with gaps predicting properties of unknown elements	By 1940 By 1950 By 1960	4 more discovered (n, e^+, μ^+, μ^-) 2 more found (π^+, π^-) Several more particles discovered; quark model proposed, predicting new particles
Early 20th century	92 elements found to fill gaps	By 1970	Predicted particles found

Revision question 8.5

What is the subatomic particle equivalent of Mendeleev's periodic table?

The periodic table initially grouped the elements by common properties, for example, metals and non-metals. Similarly the subatomic particles can be divided into groups. The two groups are leptons and hadrons, with hadrons made up of two subgroups.



The families of subatomic particles and their relationship to matter and atoms

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Leptons

Leptons are the simplest and lightest of the subatomic particles. They are fundamental particles with no internal structure.

Leptons are the simplest and lightest of the subatomic particles. The different types of leptons are shown in table 8.2.

Leptons are fundamental particles, that is, they have no internal structure, although muons and tau particles decay into electrons. The neutrinos accompany any interaction of their heavier partner.

TABLE 8.2 Leptons

Name	Symbol	Mass	Charge	First observed	Half-life
Electron	e^-		Negative	1869	Stable
Muon	μ^-	About 200 × mass of electron	Negative	1936	10^{-6} s
Tau	τ^-	About 277 × mass of electron	Negative	1977	10^{-13} s
Electron neutrino	ν_e	Negligible	Neutral	1956	Stable
Muon neutrino	ν_μ	Negligible	Neutral	1962	Stable
Tau neutrino	ν_τ	Negligible	Neutral	2000	Stable

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Antiparticles
Concept summary and practice questions

The electron is found in atoms and determines the chemical properties of elements.

The muon decays to an electron according to the equation: $m^- \rightarrow e^- + \bar{\nu}_e + \nu_m$. The $\bar{\nu}_e$ particle is an anti-electron neutrino. The bar above the symbol indicates that it is an antiparticle. *Note*: The neutrino that is produced in beta decay, that is, when a neutron decays into a proton (see page 106), is actually an anti–electron neutrino.

Muons surprisingly have industrial uses. They are more penetrating than X-rays and gamma rays, and they are non-ionising, so they are safe for humans, plants and animals. Their better penetrating power means that, for example, they can be used to investigate cargo containers for shielded nuclear material. Muons have also been used to look for hidden chambers in the pyramids. Muon detectors were used at the Fukushima nuclear complex to determine the location and amount of nuclear fuel still inside the reactors that were damaged by the Japanese tsunami in 2011.

The tau particle was discovered some time later than the muon. The unusual feature of this particle is that it decays into two pions, which are discussed later. The decay equation is $t^- \rightarrow p^- + p^0 + \nu_\tau$. The negative pion, π^-, then decays into an electron, while the neutral pion, p^0, decays to two gamma rays.

Each of the six leptons has an antiparticle. For the electron, the antiparticle is the positron. The anti-muon and the anti-tau are also positively charged.

Hadrons

Hadrons are composite particles made up of either two or three quarks.

Hadrons are distinctive because they are much heavier than the leptons, but much more importantly they all have an internal structure. Hadrons are made up of different combinations of quarks. Hadrons that are a combination of two quarks are called mesons. The other hadrons are combinations of three quarks and are called baryons.

Mesons

Mesons are hadrons with two quarks.

There are over 60 different types of **mesons**, including the pion mentioned earlier. They play a role in nuclear interactions, but have very short half-lives, so they are very difficult to detect. Each meson also has an antiparticle.

Baryons

Baryons are hadrons with three quarks.

Baryons include the proton and neutron as well as about 70 other different particles. Only the proton and neutron are stable, with all other baryons having extremely short half-lives. Each baryon also has its own antiparticle.

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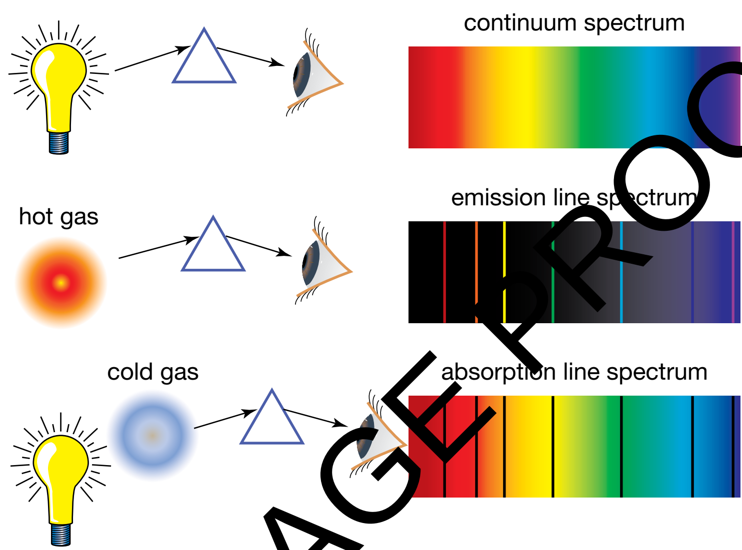
Why a quark model?

Spectra tell us something about what is inside

In the late 19th century, when visible light was shone through a gas of atoms of a particular element, a spectra of black lines was observed. Each element produced a unique pattern of these lines, called an absorption pattern.



A continuous spectrum and two different ways of producing an element's fingerprint.

On page 36, the greenhouse effect was explained by describing how H_2O and CO_2 molecules respond to particular infra-red wavelengths of electromagnetic radiation.

The lines in the atomic absorption patterns suggested that there was some complexity or structure inside the atom. This structure was discovered early in the 20th century. Similarly, the absorption patterns for H_2O and CO_2 molecules tell us something about how the molecules are put together.

More information about the internal structure of the nucleus can be determined by the energy of alpha particles emitted through radioactive decay. This energy is specific to the nucleus undergoing decay.

If a system is showing evidence that it can have only certain energy values, then it must have a structure, that is, be made up of smaller particles.

During the 1960s it was discovered that when protons and neutrons were hit by a beam of particles, a type of spectra was evident, much like molecules, atoms and nuclei. This meant that protons and neutrons are made up of even smaller particles. This was the beginning of the quark model.

In 1961, Murray Gell-Mann and Kazuhiko Nishijima developed a classification of all the known subatomic particles that, like Mendeleev's periodic table, predicted a new type of particle called a quark, which was found a few years later. Then Gell-Mann and George Zweig developed their idea further into the quark model.

AS A MATTER OF FACT

This Area of Study has described several instances where particles have been predicted and then discovered some time later. The neutron was detected 12 years after its prediction. The positron needed to wait only four years, while the neutrino took 23 years. The Higgs boson, another neutral particle, took over 50 years to be found.

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Quarks
Concept summary and practice questions

Quark model

The quark model has six different **quarks**, each with different masses and a fraction of the charge of the electron. Each quark has its own antiparticle. Quarks have rather unusual names, which are shown in table 8.3, along with their charges and mass.

Quarks are fundamental particles that combine to form hadrons.

TABLE 8.3 Quarks

Quark	Symbol	Charge	Multiple of proton mass	First observed
Up	u	$+\frac{2}{3}$	0.003	1968
Down	d	$-\frac{1}{3}$	0.006	1968
Charm	c	$+\frac{2}{3}$	1.3	1974
Strange	s	$-\frac{1}{3}$	0.1	1968
Top	t	$+\frac{2}{3}$	184	1995
Bottom	b	$-\frac{1}{3}$	4.5	1977

The top quark has the same mass as a gold atom!

AS A MATTER OF FACT

Where did the name 'quark' come from?

Murray Gell-Mann was seeking a name for the particle model he was proposing. He was reading *Finnegans Wake* by James Joyce and came across the invented word 'quark' in three lines of a poem:

Three quarks for Muster Mark!
Sure he has not got much of a bark
And sure any he has it's all beside the mark.

Where do the names for the various quarks come from?

- Up and down refer to a type of spin that characterises all subatomic particles.
- Strange quarks are components of particular baryons that were found in cosmic ray showers. They had surprisingly long half-lives and so were called 'strange particles.'
- The charm quark was so-called by its discoverers because they were 'fascinated and pleased by the symmetry its discovery brought to the subnuclear world.'
- Top and bottom quarks were named as 'logical partners for the up and down quarks.'

How do you pronounce 'quark'?

It seems there are two possibilities: one sounding like 'mark' and the other sounding like 'quart.' The pronunciation rhyming with 'mark' is the more common.

TABLE 8.4 Table of the 12 fundamental particles

	Charge	Everyday matter	Exotic matter	
Quarks	$+\frac{2}{3}$	u up	c charm	t top
	$-\frac{1}{3}$	d down	s strange	b bottom
Leptons	–1	e electron	μ muon	τ tau
	0	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino

→ mass

Mesons are composed of one quark and one antiquark. A positive pion (π^+) is made of one up quark and one down antiquark to give a charge of +1. While its antiparticle, π^-, is made of one up antiquark and one down quark to give a charge of –1. Baryons have three quarks. A proton is made up of two up quarks and one down quark to give a charge of +1. A neutron consists of one up quark and two down quarks to give a charge of zero.

Revision question 8.6

(a) The composition of the baryon called the 'charmed double bottom' is 'cbb'. What is its charge?
(b) What would you call a 'ccb' and what is its charge?

Matter and light

The word 'light' is often used as a shorthand collective for all the different types of electromagnetic radiation from radio waves to gamma rays, including infra-red, visible, ultraviolet and X-rays. It is used here in that context.

So far in this book matter has produced light in a variety of different ways. The glow of hot objects, such as the Sun, was explained by collisions between the outer electrons of atoms. The electrons' collisions with each other caused a change in direction or speed, or often both. This acceleration of the electron produced light. If the temperature was high and the accelerations sudden, then the object glowed. The same situation applies when electrons are free from their atoms or free in space.

In particle accelerators such as the Large Hadron Collider at CERN in Switzerland and the Australian Synchrotron, charged particles are accelerated by electric fields to speeds close to the speed of light, then deflected into a circular path by magnetic fields. The circular path means a constantly changing direction, so the particles are continually being accelerated and consequently giving off radiation. At CERN, this radiation and loss of energy is an unavoidable nuisance as they want very fast particles, such as protons, to smash into each other.

However, at the Australian Synchrotron, they use electrons accelerated to almost the speed of light. When electrons reach this speed, the radiation comes off in a very narrow beam along the tangent to the circular path. The radiation beam is also very intense and includes all the wavelengths across a large range. The beams at the Australian Synchrotron have a variety of uses including scientific research such as investigating the structure of proteins; medical uses such as high resolution imaging and cancer radiation therapy; as well as the analysis of mineral samples, forensic analysis and the investigation of advanced materials.

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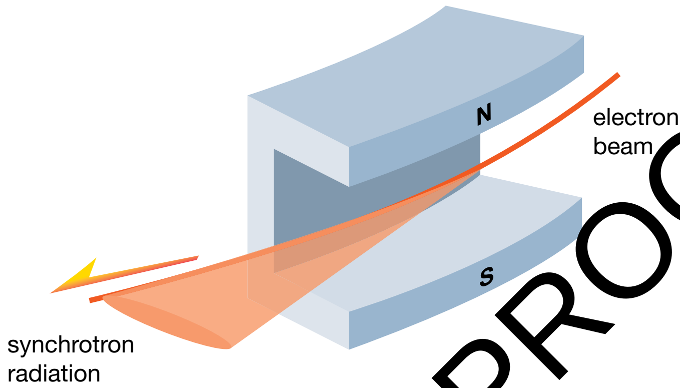
Synchrotron radiation is the electromagnetic radiation produced when electric charges are accelerated.

The name **synchrotron radiation** comes from the fact that it was first observed in 1946 when the first synchrotron was built. Since then this type of radiation has been observed in galaxies, when electrons travelling at the speed of light spiral through an intense magnetic field.



Synchrotron radiation is emitted along the tangent of the circular path.

Light from atoms

Earlier in this chapter on page 128 a figure showed a typical absorption spectrum, where light is shone through a gas and specific colours are absorbed. The figure also included an emission spectrum, where a gas is heated to a high temperature and gives a characteristic colour. The inverse of one pattern is almost identical to the other.

Each line has a specific wavelength and frequency. Consequently, the light of that colour in the spectrum has a specific energy. Each line of light in the emission spectrum has come from an electron inside the atom that has jumped from one energy level down to a lower one. The difference in energy between the two level is emitted as light energy. The existence of several lines tells us about the different energy levels that electrons in this atom can have and gives a picture of the structure inside the atom.

Revision question 8.7

Compare the light produced by a synchrotron with an emission spectrum from a hot gas for brightness and spread of wavelengths.

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Unit 1 | AOS 3 | Topic 2

Subatomic particles

Sit Topic test

Chapter review

Summary

- There are two types of fundamental particles of matter: quarks and leptons.
- There are six leptons. They are the electron, muon and tau particle, and each has its own neutrino.
- There are six quarks. They all have an electric charge, which is a fraction of the charge size of the electron. Three have a charge of $+\frac{2}{3}$, and three have a charge of $-\frac{1}{3}$. Their masses vary significantly.
- The quarks combine to form particles called hadrons, of which there are two types: mesons and baryons.
- Mesons are composed of one quark and one antiquark. There are many mesons. They can be positively charged, neutral or negatively charged, and have short half-lives.
- Baryons are composed of three quarks. There are a large number of different types of baryons, with a range of masses and charges ranging from +2 to −2.
- Some of the subatomic particles were predicted well before they were detected.
- Electromagnetic radiation is produced when electric charges are accelerated.
- Electric charges can be accelerated in a number ways to produce electromagnetic radiation.
- Very fast electrons moving in a circular path produce synchrotron radiation.
- Electrons moving between energy levels inside an atom can produce light.

Questions

Subatomic particles

1. Why do you think it has taken so long and been so difficult to find neutral particles such as the neutron, neutrino and the Higgs boson?
2. What do a particle and its antiparticle have in common? How do they differ?
3. How do mesons and baryons differ?
4. Some mesons are their own antiparticle. Explain with an example.
5. How many different mesons are possible, taking into account the previous question? How many different baryons are possible? Ignore antiparticle baryons.
6. The bottom antiquark forms a family of mesons called B mesons with each of the four lighter quarks. Determine the charge and name of each meson in this family.
7. Design baryons with:
   (a) a charge of +2
   (b) a charge of −2
   (c) a charge of zero.
8. What is the charge of:
   (a) the triple bottom baryon
   (b) the baryon that is full of charm?
9. Why do you think baryons with a top quark would be hard to detect?
10. How many baryons, in theory, could be strangely charming?
11. A neutron is described as a 'udd' and a proton as a 'uud'. What do these descriptions mean?
12. (a) The lambda baryon (Λ) was discovered by researchers at the University of Melbourne in 1950. Its quark composition is uds. What is its charge?
    (b) The lambda baryon decays into a proton (uud) and a pion ($\bar{u}$d). The quarks differ in mass. Suggest a possible mechanism for the decay.
13. A neutron (udd) can decay into a proton (uud), an electron and an antineutrino. What do you think has happened inside the neutron?
14. The heavier mesons decay into lighter mesons, which then decay into leptons. Mesons consist of two quarks. Leptons are not quarks. What does this suggest about what can happen to quarks?
15. The tau particle decays into two pions. In light of the quark model, what is unusual about this decay?
16. It is very convincing if a scientific explanation or theory can predict a future event or discovery. What are the examples of this given in this Area of Study and how significant was the discovery for the status of the explanation in each case?

Light and spectra

17. Why might different elements produce different absorption and emission spectra?
18. A gas absorbs some wavelengths of light to produce an absorption spectrum, but the light is very quickly re-emitted. Why doesn't the re-emitted light fill in the dark line?
19. The absorption and emission spectra shown in the figure on page 128 are for hydrogen, which has only one electron. Why do you think there are so many lines in the spectra?
20. In an antenna electrons oscillate backwards and forwards generating radiation. Research the type of electromagnetic radiation an antenna produces.
21. A microwave oven produces electromagnetic radiation in the microwave range. Research how microwave ovens work to find out how the electrons are accelerated.

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