CHAPTER 29

Quantum Physics and Fundamental Particles

29.1 INTRODUCTION

Until the end of the nineteenth century, classical physics, based on the laws of Newton, had sufficed to explain all our natural surroundings of matter, space and time. It was at the turn of the century that the experimental observations by physicists and subsequent theoretical explorations began to question the validity of the Newtonian laws, especially at very small distances, very high speeds and within the world of the emerging atom. For example, lines had been noticed in the spectra of light emitted by heated gases or gas discharges. The Rutherford atomic model would not have predicted these lines. Light itself was difficult to explain as it seemed to have both a particle nature and a wave nature, and the field of thermodynamics did not seem to be related to molecules and atoms at all.

The original hypotheses and theories evolved over the twentieth century into two great pillars of theoretical thinking and analysis. Today, these pillars of physics are called 'quantum theory' or **quantum mechanics**, and **general relativity**. Along the way, it has taken the profound thoughts of dozens of brilliant minds in physics to bring these theories to their present stage of development. In this chapter, we will take a short glimpse at some of this historical work. Sometimes the path is highly intertwined, but it is never boring. Both of these theories have given us a picture of our surroundings, from the infinitesimally small subnuclear domain within the atom to the vast reaches of space and the nature of the universe itself. The two great theories are independent:

- General relativity successfully describes the motion and behaviour of bulk matter and its gravitational interaction by the radiation of gravity waves.
- Quantum theory successfully explains the behaviour of subatomic matter in terms of constituent particles and their force interactions, which has culminated in the **standard model** of particle physics.

Standard quantum theory

Standard quantum theory today gives us three fundamental forces. These act between, and within, individual atoms of matter that are made up of twelve basic particles. These forces are:

- the **electromagnetic force**, which holds the electrons within the atom
- the **strong nuclear force**, which binds the nucleus together
- the **weak nuclear force**, responsible for radioactive decay and the interactions of nature's most amazing particle, the neutrino.

A fourth fundamental force is called the **gravitational force**. Gravity acts over huge distances and holds the universe together. It is in the realm of general relativity and space–time. Gravity, surprisingly enough, is the least well understood, despite the efforts of Newton and Einstein. This force is still the odd one out in a grand unified theory of everything, or '**TOE**' as physicists call it. Physics will need in the future to develop a concise TOE if it is to answer the big questions of — Who we are? What we are? and Where we are? Famous physicists, such as Stephen Hawking and colleagues, are working to combine quantum theory and general relativity, but it is complex theoretical work. Let's go back to the start!

Planck's black body radiation

At the beginning of the last century, interesting experiments were being performed on the nature of the radiation emitted by a **black body**. A black metallic object will not reflect any light shining onto it, so as it is heated, any light radiation that it emits is solely coming from within itself. A good example is the electric hotplate of a stove, which begins to glow red, then orange and even white if it is allowed to become hot enough. The distribution of intensity versus frequency of light emitted for this type of hot body is given in Figure 29.1.

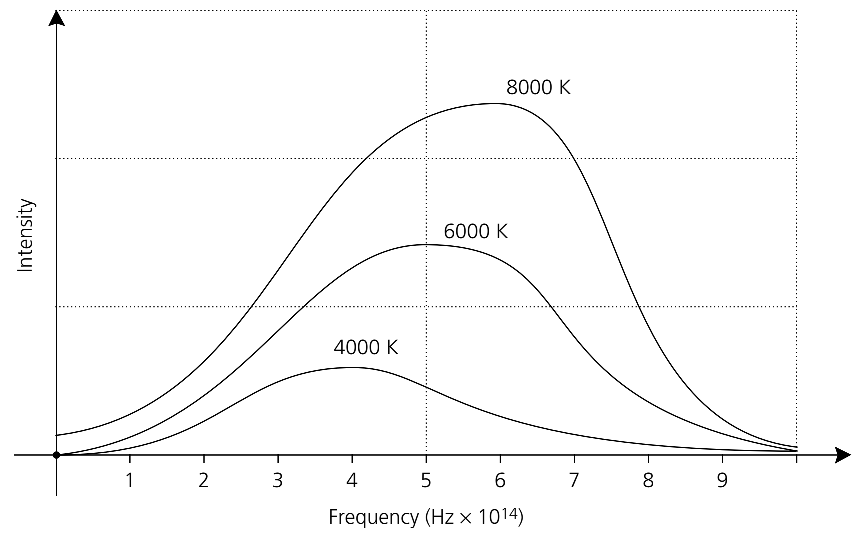


Figure 29.1
Black body radiation.

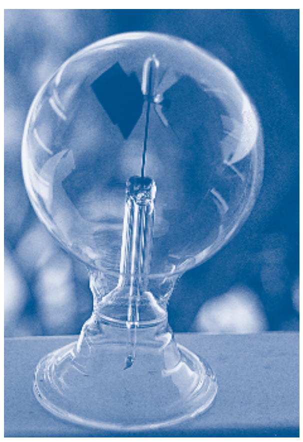


Photo 29.1
Crookes' radiometer with the black and white vanes clearly visible.

The shapes of these graphs at different temperatures went against all theoretical predictions based on James Clerk Maxwell's electromagnetic theories. Questions such as, 'Why weren't ultraviolet, X-rays or gamma rays produced?' or 'Why was there more red frequency radiation than blue?' could not be satisfactorily answered. Physicists such as Robert Kirchhoff and Nobel laureates John Rayleigh and Wilhelm Wien had produced equations that described only parts of these distribution curves, but none could satisfactorily describe the whole range.

A German physicist, **Max Planck** (1858–1947), finally produced the equation that did describe the black body distribution, and in doing so, he proposed a revolutionary theory of subatomic matter. Planck proposed that the energy released by a black body was, in fact, emitted by atoms, and that these atoms could only vibrate at certain frequencies that were multiples of some smallest value. He had to assume that the energy released by the atoms was not given off continuously, but in small energy packets that he called **quanta** (singular quantum), from the Latin *quantus*, meaning 'how much'. Each frequency, f, of light emitted by the atoms is proportional to the change in energy of the atom, so that, for example, since violet light is twice the frequency of red light, the energy quanta of violet light are twice the size of those of red light. Mathematically, the quanta energy is given by $E = hf$, where the constant h is called the **Planck constant** and has a value of 6.63×10^{-34} J s. Since the Planck constant is extremely small in magnitude, energy quanta are not noticeable in most everyday circumstances. A typical light source such as an incandescent bulb releases millions of quanta per second, which lead to the amount of light energy that we are familiar with.

With this idea in place, Planck was able to describe the reason for the absence of high energy emissions from black bodies. The vibrating atoms were simply not large enough to

NOVEL CHALLENGE

A Crookes' radiometer consists of four paddles suspended on a needle point in a low pressure glass container. One side of the paddle is painted black, the other side white. When placed in the Sun it turns around. *Explain whether the black side moves away from the sun or towards it (and why)*. It goes the opposite way near a block of dry ice (−44°C). Most people (even scientists) gave the wrong explanation. Check our web page and all will be revealed.

provide the necessary energy changes. Also, certain states of vibration of the atoms were more likely and this accounted for the peak in the frequency distribution curves. As we will see later, Planck's idea that the whole atom vibrates is, in fact, not quite correct. Energy emissions are due to electron movements (transitions) within the atom. Quantum theory today shows that electrons in atoms can only move between defined energy levels within the atom. Planck himself did not have any evidence for energy quanta, but it was an excellent idea that perfectly described solutions to several problems in physics at the time. The quantum theory has provided the basis for all modern physics since 1900 and for his work, Max Planck received the 1918 Nobel prize for physics. It now remained for the quantum idea to be applied to both light and matter.

Light itself can be assumed to come in small packets called **photons**, which give light radiation a reason for behaving like particle systems, under certain conditions. If light radiation is governed by the wave equation for velocity, c, frequency and wavelength, namely $c = f\lambda$, then light photons will have energy given by:

$$E = hf = \frac{hc}{\lambda}$$

Note: c is the velocity of electromagnetic radiation (light) and equals 3.0×10^8 m s^{-1}.

NOVEL CHALLENGE

The **photon** was named by US physicist Gilbert Lewis in 1926 using the Greek *phos*, meaning 'light'. See if you can prove these statements wrong (we doubt you can):

A All words beginning with the prefix *phos* are related to the concept of light.

B The planet Venus used to be called Phosphor when appearing as the morning star.

The photoelectric effect

Further proof of the quantum idea came when **Albert Einstein** (1879–1955) applied the theory to explain the **photoelectric effect**. When a metal surface is illuminated by a high-frequency light source, electrons may be ejected from the metal as a **photocurrent** with definite characteristics (Figure 29.2). Experiments on this effect, by physicists from as early as 1887, had confirmed that electrons were ejected from the metal only if the frequency of the incident light exceeded a minimum value called the **threshold frequency**, f_0, which was different for various metals. Even very intense light, if the frequency was below the threshold value, would not eject electrons and cause the flow of the photocurrent. Two other important characteristics of the photoelectric effect are:

- Once a photocurrent is registered, increasing the incident light intensity increases the amount of photocurrent flowing.
- Light of a higher frequency than that required to produce a photocurrent increases the kinetic energy of the ejected electrons.

The electron kinetic energy is measured by a negative potential applied to the collector plate, which repels the ejected electrons and eventually becomes large enough to stop the photocurrent. This reverse **cut-off voltage**, V_c, applied to the collecting plates in the electron tube is also called the **stopping potential**. This is the opposite to an electron gun.

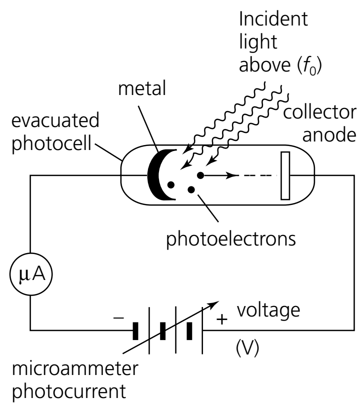


Figure 29.2
Photoelectric apparatus.

Each of these experimental observations was impossible to explain using conventional wave theories of light. Einstein applied the newly developed quantum theory to this effect in 1905, and provided the perfect explanation. His explanation revived the light particle model, and for this effort he was later awarded the Nobel prize for physics in 1921.

Einstein assumed that the light quanta, called photons, interacted with the surface electrons in the metal so that a single photon ejects a single electron. The photon will give either all of its energy to the electron or none of it. Each electron can only absorb the energy of one photon and the collision interactions between photons and electrons in the metal are totally elastic and obey the law of conservation of energy. Einstein defined three forms of energy in the system, namely:

- photon energy, $E = hf$, which is frequency-dependent
- work function or energy of binding of the electron to the metal, which is measured as $W = hf_0$, where f_0 is the threshold frequency
- maximum kinetic energy, $E_{K(max)}$, of the ejected electrons from the metal surface.

NOVEL CHALLENGE

At night, turn all the lights off and turn the oven element ON. Feel the heat before it glows. Watch the element glow and see how it changes from red to red/orange. In furnaces, the elements change colour further and end up almost white.
If the blue–violet end of the spectrum indicates higher energy, why doesn't the element go red → blue instead of red → white?

Einstein's photoelectric equation relates these energy values together such that conservation occurs, namely:

$$E_{K(max)} = hf - W$$

or

$$\left(\frac{1}{2}mv^2\right) = hf - hf_0 = qV_c$$

where V_c is the cut-off voltage necessary to reduce the flowing photocurrent to zero; v is the ejected electron velocity.

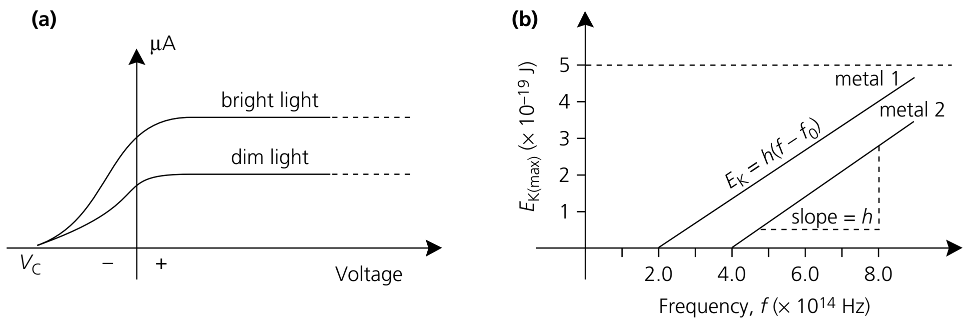


Figure 29.3 Results from photoelectric experiments: **(a)** I/V characteristics; **(b)** $E_{K\ MAX}$/frequency.

NOVEL CHALLENGE

In a dark room let your eyes become dark-adapted. Give your eyelid a sharp tap with your finger and you should see a flash. A single rod will detect a single photon, but your visual system only responds when between two and ten photons are absorbed by your rods within 0.1 seconds; you will then see the flash. Estimate how much power two visible photons will give to your eyes in 0.1 seconds.

Figure 29.3 represents a typical set of graphs obtained from photoelectric experiments carried out on various metals. Notice that the slope of the straight lines of graph **(b)** can be used to calculate the value of Planck's constant. This experimental determination of h was first performed by Robert Millikan in 1916.

The quantum theory was by now well and truly established both in theory and in experiment. The term photoelectric effect can be applied equally well to other phenomena such as photoionisation in gases, whereby light radiation can ionise gas atoms, or photoconduction where incident light photons are absorbed by various crystalline materials, giving their electrons enough energy to break free and become electrical conductors. Today, photovoltaic semiconductor materials are common, such as solar cells, photo diodes and transistors. In these materials, incident light photons of sufficient energy create electron-hole pairs in the crystal and increase electrical conduction. Refer back to Chapter 23.

Questions

1 What are the four fundamental forces in nature? On what do they each act? Which has the biggest range, and the smallest range?

2 Calculate the energy and wavelength of light of frequency 4.3×10^{14} Hz. What colour would it appear to our eye?

3 Which light has the more energetic photons, red or violet? Explain why.

4 If the threshold frequency for rubidium metal is 5.0×10^{14} Hz, calculate the value of the work function of the metal and the maximum velocity of photoejected electrons when the metal is illuminated by light photons of frequency 8.1×10^{14} Hz. The mass of the electron is 9.11×10^{-31} kg.

The Compton effect and light pressure

Further evidence for the particle nature of electromagnetic radiation came with the discovery of X-ray scattering, by **Arthur Holly Compton** (1892–1962). Compton used apparatus as shown in Figure 29.4, and showed that the X-ray photons behaved like particles with definite momentum characteristics. The X-rays collided with the electrons in the graphite target. The scattered X-ray photons, after collision, possessed reduced energy and longer wavelengths when compared with the unscattered photons. In a **Compton collision**, between an X-ray photon and an electron, the change in energy is not complete and the reduction in energy

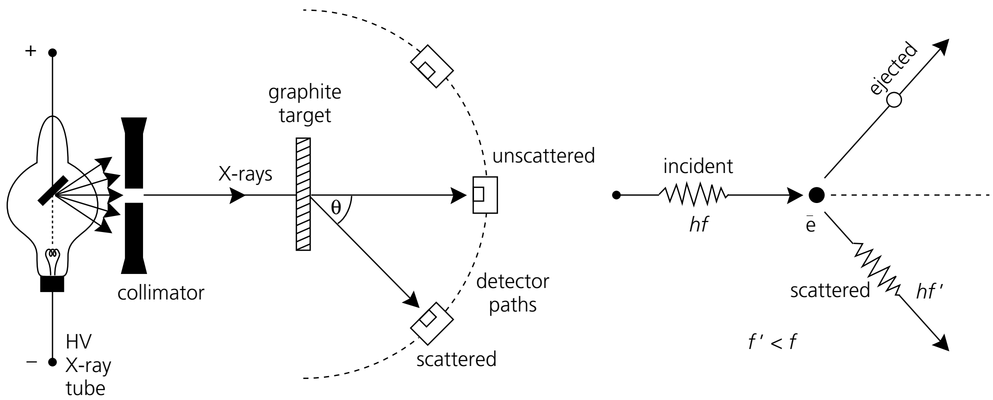


Figure 29.4
Compton scattering.

and wavelength is dependent on the angle of scattering. The electron involved is scattered or ejected from the graphite in such a way that both energy and momentum are conserved in the collision. Remember that momentum is a vector quantity. Compton's collision calculations correctly predicted the speed and direction of the recoil electrons. For this work, as well as further X-ray spectra analysis, Compton shared the 1927 Nobel prize for physics with British physicist Charles Wilson.

When considering the photon as a particle, we can derive a formula for the photon momentum. Einstein's mass–energy equivalence relationship $E = mc^2$ links the idea of physical mass to energy; however, the quantum idea states that photon energy is $E = hf$, thus the photon particle energy will be:

$$E = mc^2 = hf$$

or

$$mc = \frac{hf}{c}$$

But mc is the definition of photon momentum, p, hence:

$$p = \frac{hf}{c} = \frac{h}{\lambda} \text{ where } c = f\lambda$$

Since light or electromagnetic photons have momentum, $p = \frac{h}{\lambda}$, then, in collisions with surfaces, they should be able to exert a force and create **light pressure**. This is exactly what does occur in practice. The pressure exerted depends on the rate of change of momentum per unit area of illuminated surface. The pressure of light is extremely small at the Earth's surface. It is a factor of 2.5×10^{10} less than standard atmospheric pressure. As early as 1903, Edward Nichols and George Hull measured light pressure using mirrors and a sensitive suspended fibre torsion balance, achieving a result of 7.01×10^{-6} N m^{-2}.

The revolution in thinking caused by the quantum theory and its successful application to black body radiation, the photoelectric effect and X-ray Compton scattering, caused electromagnetic energy to be given a dual nature by physicists. The **wave–particle duality** concept for light and other forms of electromagnetic energy is our current explanation. If we are describing what light is (!) then we need to consider what we are explaining. In general, if light energy is interacting with other forms of light energy, then the wave behaviour model is the best explanation, as, for example, in optical effects such as interference and diffraction. If light is interacting with matter, then the particle behaviour model is the best explanation, as, for example in Compton collisions. The mathematical model bringing together the wave–particle duality concept used to describe matter and energy is called wave mechanics or quantum mechanics and will be discussed further in Section 29.4. First, before taking a look at these ideas, let's further investigate the models and theories applying to the atom and see how the quantum idea is vitally important here also.

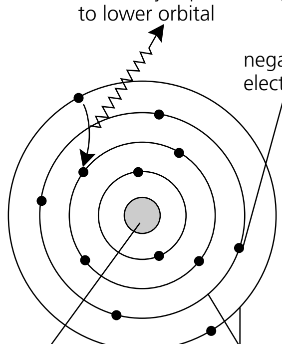
THE BOHR ATOM AND ATOMIC SPECTRA 29.3

In 1911, the New Zealand-born British physicist Ernest Rutherford had established the existence of the atomic nucleus, and he made it possible to consider the simplest atom of hydrogen as a single positive charge with a single negative electron circling it in planetary fashion. This atomic model had a serious flaw in that, according to the electromagnetic equations of Maxwell, any electron revolving in circular fashion around a nucleus is under centripetal acceleration and should continuously radiate electromagnetic energy. This would allow the electron to continuously lose energy and cause it to spiral in toward the nucleus. Thus, the equations predicted that the Rutherford atom should be highly unstable and not exist for any length of time as it would quickly lose its energy and collapse. Clearly, this was not what actually happens.

In 1913, Danish physicist Niels Bohr applied the quantum concept to the problem and proposed a revolutionary hypothesis. His idea was that the electron would only radiate energy in exact quanta or definite amounts of energy. As it did so, it would move inward toward the nucleus in definite **quantum orbitals** or allowed orbits until a stable orbit was reached. This stable orbit is called a **stationary state**. Normal atoms exist with their electrons in stationary states, but if energy is added to any atom, such as by particle bombardment or sufficient heating, then the electrons are forced into higher energy states (orbitals) temporarily by absorbing definite quanta. This process of absorption produces an **excitation energy** state. As the atom restabilises, the electron jumps back down to a stationary state in a possible series of steps. Each orbital jump results in the emission of a photon of electromagnetic energy of definite predictable value.

Thus, every change in orbit by an electron corresponds to the absorption or emission of a quantum of electromagnetic radiation. (Refer to Figure 29.5.) If an atom absorbs too much energy then the outermost electron will be promoted completely away from the attraction of the nucleus and will be lost. This is called **ionisation energy** and for the simplest hydrogen atom is equal to 2.17×10^{-18} J. Bohr also proposed that within the atom only two electrons could occupy the same orbital at any one time. Further work on this idea resulted in the **Pauli exclusion principle** and it became possible to show that atoms are arranged in the periodic table as a result of electrons being arranged in definite patterns from the lowest energy orbitals outward.

Figure 29.5
The Bohr atomic model.



The **spectrum** or range of emitted light released by hydrogen gas atoms had been known since 1885 when Johann Balmer, a Swiss physicist, had worked out a mathematical link between the wavelengths of the light colours emitted. You should recall that the component wavelengths of any light source can be examined by passing the light through a **prism spectrometer**, which splits the light into its spectral colour components. Niels Bohr could now choose orbits for the hydrogen electron that would yield exactly the required wavelengths for the emitted spectral lines of the hydrogen spectrum, according to the generalised Balmer equation:

$$\frac{1}{\lambda} = R_H\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$$

where R_H is the Rydberg constant (1.097×10^{7} m^{-1}); n_f and n_i are the initial and final **principal quantum numbers**.

Figure 29.6 represents the **energy level diagram** for hydrogen that correlates the Bohr orbitals and their corresponding energies with the series of spectral lines present in the hydrogen spectrum. The spectral series are named after their discoverers.

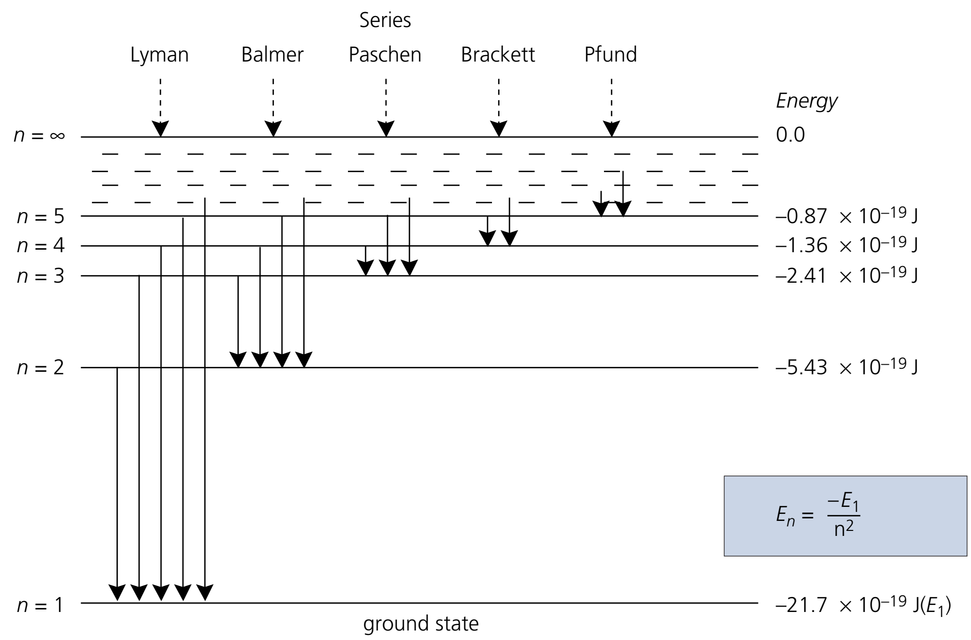


Figure 29.6
Energy level diagram for hydrogen.

Mathematically, Bohr's theory used a **quantum condition** that specified that the angular momentum of the electron was restricted to allowed orbits, given by:

$$mvr_n = \frac{nh}{2\pi}$$

where $n = 1, 2, 3 \ldots$ integers; r_n is the radius of the n^{th} orbit.

He was able to show that, at least for the simplest hydrogen atom, the radius of the electron for each quantum orbital possible is given by:

$$r_n = \frac{n^2h^2}{4\pi^2kmq^2}$$

where n is the principal number; k is the Coulomb constant; m, q are electron mass and charge.

Thus, for $n = 1$, the **Bohr radius** takes a value of 5.3×10^{-11} m, and represents the orbital radius for the electron in the lowest energy state or **ground state** of the hydrogen atom. Notice that in the energy level diagram of atomic hydrogen, the energy associated with the ground state is a negative value of -21.7×10^{-19} J and represents the ionisation energy for hydrogen. In order to remove an electron out to infinity, this amount of energy is required. Because we can say that the electron at infinity has zero energy, by definition, all possible energy states of the hydrogen atom can be regarded as negative. According to the Bohr theory, the energy of each quantum orbital is given by the series:

$$E_n = E_1\left(\frac{1}{n^2}\right) \text{ where } E_1 \text{ is the ground state energy}$$

$$E_1 = -2.17 \times 10^{-18} \text{ J or } -13.6 \text{ eV (electronvolts)}$$

Notice that other spectral series represented in the hydrogen spectrum are named after the people who discovered them. It is only the Balmer series of jumps back to $n = 2$ that represents visible light emissions. You might like to check this out, using an energy–wavelength calculation.

Bohr's theory was very good at predicting the spectral line series of the hydrogen atom, but could not correctly predict those for more complex atoms, nor could it predict other observable features such as spectral line intensity differences and fine splitting of the lines themselves within a magnetic field. Even the basic notion of why the electron oscillated only within defined quantum orbitals could not be explained. Nevertheless, his application of the quantum theory to atomic structure was very important and, for his work, Bohr gained the 1922 Nobel prize for physics. Today, the newly discovered artificial radioactive element of atomic number 107 is called **Nielsbohrium** (Ns). The isotope was discovered by a Soviet group at Dubna in 1976 by bombarding bismuth with chromium ions to form $^{261}_{107}$Ns.

NOVEL CHALLENGE

We read in a US science magazine that if you shone a laser beam onto glow-in-the-dark plastic it would go dark (yes, dark!) where the laser hit. This sounds like rubbish, but we tried it. What do you think happened?

Example

(a) Determine the energy of an electron in both the fourth and second quantum orbitals of the hydrogen atom.

(b) What is the frequency of the energy emitted when an electron jumps between these orbitals?

(c) Calculate the wavelength of this emitted light **(i)** in metres, **(ii)** in nanometres.

Solution

(a) Fourth level $n = 4$.

$$E_4 = \frac{E_1}{4^2} = \frac{-2.17 \times 10^{-18}}{16} = -1.36 \times 10^{-19} \text{ J}$$

Second level $n = 2$.

$$E_2 = \frac{E_1}{2^2} = \frac{-2.17 \times 10^{-18}}{4} = -5.34 \times 10^{-19} \text{ J}$$

Electron jump, energy released is:

$$\Delta E = E_\text{i} - E_\text{f} = E_4 - E_2$$
$$\Delta E = 4.07 \times 10^{-19} \text{ J}$$

(b) Use the equation $\Delta E = hf$ or $f = \frac{\Delta E}{h}$

$$f = \frac{4.07 \times 10^{-19}}{6.63 \times 10^{-34}} = 6.14 \times 10^{14} \text{ Hz}$$

which represents the Balmer series line of colour blue.

(c) Use the equation $v = f\lambda$ or $= \frac{v}{f}$

$$\lambda = \frac{3 \times 10^{8}}{6.14 \times 10^{14}} = 4.88 \times 10^{-7} \text{ m}$$

Convert to nanometers: 4.88×10^{-7} m $= 488 \times 10^{-9}$ m $= 488$ nm

Franck–Hertz experiment

In 1914 two German physicists, James Franck and Gustav Hertz, the nephew of Heinrich Hertz, performed a very important experiment that supported Bohr's ideas on quantum atomic absorption and emission. Their apparatus is represented in Figure 29.7. Your school laboratory probably has a demonstration electronic valve apparatus that can be used to obtain similar results. The glass chamber contains mercury vapour at a low pressure of about

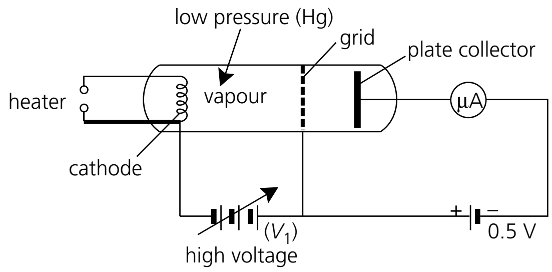


Figure 29.7
The Franck–Hertz apparatus.

1.0 mm Hg. A hot cathode emits electrons towards a mesh grid that is maintained at some variable potential with respect to the cathode. Beyond the grid mesh is a solid metal plate maintained at about negative 0.5 V with respect to the grid that collected the high energy electrons and allowed the measurement of tube current by the microammeter. The experiment involved gradually increasing potential V_1 and noting the tube output current. Typical results are shown graphically in Figure 29.8, which consists of a series of current peaks and troughs separated by an average value of 4.9 V.

Franck and Hertz explained these results in terms of quantum absorption. At voltages below 4.9 V, the electrons interact elastically with the mercury atoms. At 4.9 V, the electrons transfer most of their energy to the mercury atoms because the first excitation energy for mercury is 4.86 eV. They now do not have enough energy to reach the collecting plate and the current falls into a trough. If the voltage is increased again, the electrons gain enough energy to reach the plate again. At 9.8 V, the electrons can make two inelastic collisions with the mercury atoms and so the current falls again into a trough. If the spectrum of the mercury is examined, an ultraviolet line can be found at 253 nm, which corresponds to the emission from the atoms of photons of energy 4.9 eV as they return to their ground state. It is this wavelength that is produced in a fluorescent light tube and converted to white light by the phosphor coating on the inside of the glass tube itself.

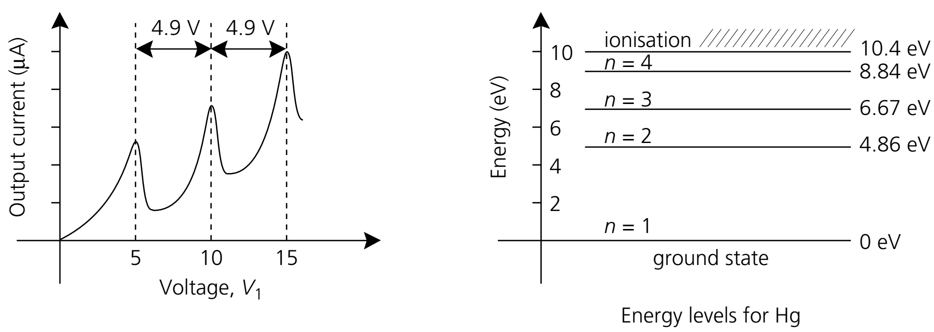


Figure 29.8
Graphical results of the Franck–Hertz experiment and the energy level diagram for mercury.

The Franck–Hertz experiment verified that atoms contain discrete energy levels and cannot absorb random amounts of energy. The colliding electrons lose energy only in discrete quantum chunks corresponding to precise energy differences between the atom's energy states. This same energy quantum is reradiated as a precise single wavelength when the excited mercury atom returns to its ground state. Figure 29.8 illustrates the energy level diagram for mercury. It should be realised at this point that every atom has its own characteristic energy level diagram and thus the excitation spectra will be like an atomic fingerprint. (See the photo in the colour section.)

NOVEL CHALLENGE

In 1800, English astronomer William Herschel placed a thermometer in various parts of the spectrum of sunlight. He found that the highest temperature was beside the red where there was no colour. Explain that if you can.

Spectroscopy

Spectroscopy is used in analytical processes to definitively identify individual atoms or molecules. It is a very powerful technique. The word spectrum comes from the Latin *specere* meaning 'to look at'. The first prism spectroscope was, in fact, designed by Gustav Kirchhoff and Robert Bunsen in 1859 while working on chemical analysis.

When light from a hydrogen discharge tube is examined through a spectroscope, distinct lines appear on a black background, each one corresponding to an electron transition in the hydrogen atom. (See Figure 29.9 below.)

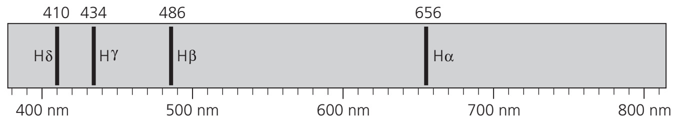


Figure 29.9
The spectrum of hydrogen shows the four lines of the Balmer series, all of which are in the visible region.

As mentioned previously, four of the lines (the Balmer series) are in the visible region. They are labelled alpha, beta, gamma and delta and correspond to the following transitions:

Table 29.1

LABEL	TRANSITION	ENERGY OF PHOTON (J)	FREQUENCY (Hz)	WAVELENGTH (nm)	COLOUR
H_α	$3 \rightarrow 2$	3.02×10^{-19}	4.57×10^{14}	656	red
H_β	$4 \rightarrow 2$	4.09×10^{-19}	6.17×10^{14}	486	green
H_γ	$5 \rightarrow 2$	4.58×10^{-19}	6.91×10^{14}	434	blue
H_δ	$6 \rightarrow 2$	4.85×10^{-19}	7.31×10^{14}	410	violet

When physicists turned their spectrometers towards the heavens and examined the spectra of starlight they found spectral lines characteristic of elements they had examined on Earth. The spectra of hydrogen and helium were particularly noticeable, but other elements such as calcium gave strong lines in their spectrometers. Astronomers were thus able to infer the composition of stars from their spectral signatures. But what was most astonishing was that many of the characteristic patterns were shifted towards the red end (low wavelength) of the spectrum. The term 'red shift' was coined to describe this phenomenon.

Recalling that the frequency of a sound changes as a source moves in relation to an observer, physicists used this very same Doppler effect (see Chapter 16, Section 13) to propose that the red shift was due to the motion of stars speeding away (receding) from us. This is called **radial** or **recessional velocity** (RV).

In a star that is at rest with respect to us (the Sun), or in a hydrogen discharge tube in the laboratory, the hydrogen line wavelengths are 410, 434, 486 and 656 nm. By measuring the amount of shift towards the red, we can determine how fast the star or galaxy is moving away. For example, Figure 29.10 shows the line spectrum of standard hydrogen (Spectrum I) and for two objects that have red-shifted spectra.

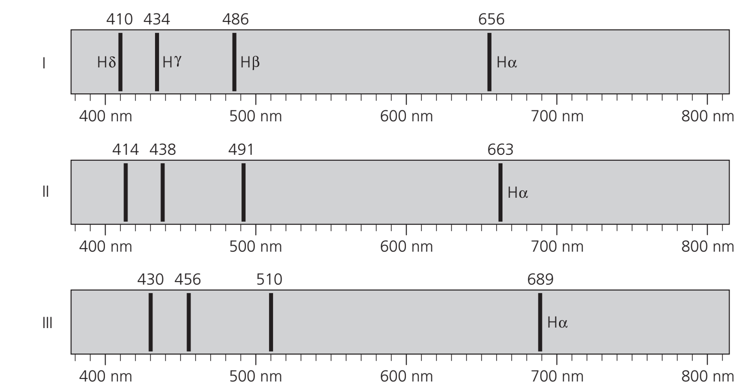


Figure 29.10
Comparison of hydrogen spectra from a laboratory source (I) and from stars speeding away from us (II and III). Note the red shift.

Spectrum II is for the galaxy Centaurus. Note that the Hα line is red-shifted by 7 nm from the standard 656 nm to 663 nm. A shift of 7 nm from 656 nm is a ratio of 7/656 or 0.01, which means the galaxy is travelling away from us at 0.01 times the speed of light (0.01*c*). This corresponds to a speed of 3200 km s^{-1}. The other hydrogen lines are shifted by the same ratio.

The red shift z is defined such that:

$$z = \frac{\lambda_0 - \lambda}{\lambda_0} = \frac{\Delta\lambda}{\lambda_0} = \frac{v}{c}\text{, so } v = c\frac{\Delta\lambda}{\lambda_0} = cz$$

Example

Spectrum III is for the galaxy Ursa Major I. Calculate its radial velocity.

Solution

The Hα line has been shifted from 656 nm (λ_o) to 689 nm (λ), hence $\Delta\lambda$ = 23 nm. The red shift ratio (z) = 23/656 = 0.05, so it is moving at 0.05 times the speed of light (0.05c) away from us. This equals 10 500 km s^{-1}.

Note that this equation only works for galaxies moving a few tenths the speed of light or slower. Those with large z values need a relativistic version of the above equation:

$$1 + z = \sqrt{\frac{1 + \frac{v}{c}}{1 - \frac{v}{c}}}$$

If you want a challenge, show that the speed of the galactic cluster named 3C295 is actually 0.46c (using the relativistic formula), not 1.64c as predicted using the non-relativistic formula. The Hα line has an observed wavelength of 1076 nm.

When z is larger than 1, cz is faster than the speed of light, and while recessional velocities faster than light are allowed, this approximation using cz as the radial velocity of an object is no longer valid. Thus for the largest known red shift of z = 6.3, the recessional velocity is not 6.3c = 1 890 000 km s^{-1}. It is also not the 285 254 km s^{-1} given by the special relativistic Doppler formula. The actual recessional velocity for this object depends on the cosmological parameter omega (Ω) which is a measure of the expansion of the universe (see Chapter 6).

Activity 29.1 IN A GALAXY FAR, FAR AWAY...

1 The spectrum of light from the galaxy Hydra is shown in Figure 29.11. Compare the radial velocity of Hydra as calculated by using both the non-relativistic and relativistic formulas.

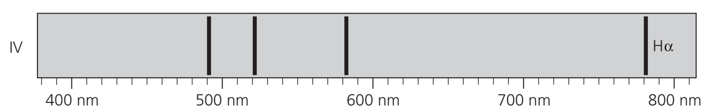


Figure 29.11
Spectrum of the galaxy Hydra.

2 The calcium-K line and the calcium-H line for the galaxy Leo are 419 nm and 398 nm respectively. Locate the standard Ca-K and Ca-H wavelengths and calculate the velocity of Leo.

3 The galaxy Persus is known to have a radial velocity of 5430 km s^{-1}. Draw a simple line spectrum to show the relative spacing of the four hydrogen lines in Persus's spectrum.

Questions

5 Show that the emitted photon from a mercury atom dropping from its first excitation energy level to the ground state is, in fact, an ultraviolet photon.

6 Is it fair to say that Compton scattering between photons and electrons is like billiard balls colliding? Explain.

NOVEL CHALLENGE

In 1801, German scientist J. W. Ritter put a piece of photographic paper in the spectrum of sunlight and found that the greatest blackening was beside violet where there was no colour. Explain that if you can.

7 Define these terms as applied to quantum atomic theory: **(a)** quantum orbital; **(b)** excitation energy; **(c)** ionisation energy; **(d)** principal quantum number; **(e)** Nielsbohrium.

8 Calculate the wavelengths of the first three lines of the Lyman series in the spectrum of hydrogen. To what part of the electromagnetic spectrum do they belong? (See Figure 29.6.)

9 Explain why the spectrum of hydrogen contains several very bright lines while the atom itself contains only one electron and one proton.

10 In a Franck–Hertz experiment carried out with potassium vapour, it is found that current falls off rapidly at an applied voltage of 1.62 V. Calculate the wavelength of the expected spectral line in the emission spectrum of potassium when this voltage is reached.

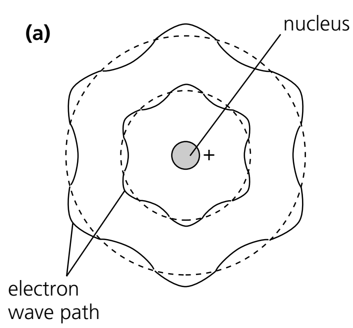
Activity 29.2 SPECTACULAR COLOURS

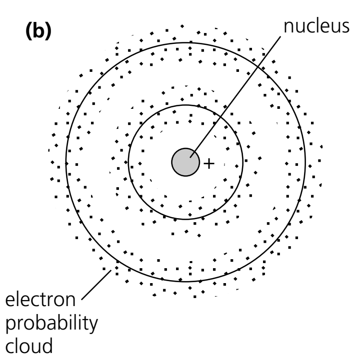
1 Set up some spectrum discharge tubes using a high voltage induction coil. Obtain your teacher's assistance to do this and use a simple direct vision spectroscope or diffraction grating to observe the spectra. Note both the colour to the eye and the primary lines of the emission spectra. You should try gases such as H_2, He, Ne, CO_2.

2 Placing small amounts of crystalline ionic salts (preferably chlorides) into the flame of a bunsen burner using a clean platinum loop provides a display of characteristic metallic atom spectral colours. Use this to explain the brilliant colours of fireworks.

QUANTUM MECHANICS 29.4

Figure 29.12
Electron standing waves: **(a)** orbital wavelengths; **(b)** electron clouds.





The problem of how an electron could exist in quantum orbitals without losing energy was solved in 1924 when the French physicist Louis Victor de Broglie suggested that matter could also exhibit wave-like characteristics. He called these **matter waves**. Louis de Broglie postulated that an electron particle could have a wavelength $\lambda = \dfrac{h}{mv}$, just as the photon has a wavelength $\lambda = \dfrac{h}{p}$ as a result of its momentum.

This idea allowed Bohr's quantum orbitals to be considered as electron wave orbits whose circumference contained an integral number of wavelengths (Figure 29.12**(a)**). The **standing waves** of the electrons in orbit would not require any loss of energy and the angular momentum of the electrons in their orbits is quantised. This de Broglie prediction was experimentally verified by the American team of Clinton Davisson and Lester Germer, as well as the British physicist George Thomson. They showed that a beam of electrons scattered by crystals does, in fact, produce a characteristic wave diffraction pattern.

The de Broglie wavelengths of anything, except subatomic particles, are very short. It makes little sense, for instance, to think of the de Broglie wavelength of a Ford Fairlane driving down the road at 80 km h^{-1} even though such a quantity exists. Assuming a mass of 1642 kg for the car, show that the de Broglie wavelength is 1.8×10^{-38} m. In practice, this value is immeasurably small and can be neglected.

The wave particle concept has led to very complex mathematical models of the nature of atomic structure, called wave mechanics. **Wave equations**, developed by the Austrian physicist Erwin Schrödinger, describe the wave properties of electrons in both hydrogen and helium atoms. The solutions of Schrödinger's wave equations also indicate that no two electrons can possess the same set of characteristics defined by quantum numbers. This verified the exclusion principle established by Wolfgang Pauli in 1925. Further mathematical refinements by German theorists Max Born, Ernst Jordan and Werner Heisenberg led to 'matrix mechanics' theory, which is very successful in making predictions about atomic behaviour.

Although quantum mechanics describes an atom in purely mathematical terms, a verbal description and a visual model can be constructed for our modern view of the atom. Surrounding the dense nucleus of any atom is a series of standing wave electron orbitals with wave crests at certain points. The square of the wave amplitude at any point is a measure of the **probability** that an electron can be found at that point at any given time. This gives us a picture of an **electron cloud** around the nucleus. (See Figure 29.12**(b)**.) This probability is as good as we can get to defining the position of any electron and is a result of the **uncertainty principle**, developed by Werner Heisenberg in 1927. His work pointed out that any measurement made on a physical system will, in fact, change the system itself and introduce a fundamental uncertainty into measurements of all other properties of that system. Heisenberg was awarded the 1932 Nobel prize for physics for his contribution to quantum mechanics. There is a hotel in England with an inscription above the door that reads 'Heisenberg may have slept here!'

The principle states: 'It is impossible to measure the position and the corresponding momentum of a particle simultaneously with complete accuracy. The product of the uncertainty in the position and momentum is greater than, or at best equal to, $h/4\pi$.'

Mathematically: $$\Delta x \, \Delta p = \frac{h}{4\pi}$$

Again, it might be obvious that this effect is really only important in the subatomic domain. For example, if an electron is measured with a velocity of 4.4×10^6 m s^{-1}, with an uncertainty of 0.1%, then the value $\Delta x = 1.3 \times 10^{-8}$ m represents the positional uncertainty of the electron. Check it out. This uncertainty is, in fact, about 100 times the diameter of the hydrogen atom, so this principle will not even allow us to determine if the electron is within the atom. The uncertainty principle places large limits on measurement of atomic properties.

Quantum mechanics has solved a lot of the great scientific problems that have troubled physicists. It is interesting to note, however, that even Albert Einstein had difficulties with the ideas of quantum mechanics and had many famous arguments with Niels Bohr on the subject. It was Einstein, though, who proposed Heisenberg for the Nobel prize with the endorsement: 'I am convinced that this theory undoubtedly contains part of the ultimate truth'. Perhaps one of the most striking features of quantum physics that has only recently been discovered is that it is not possible in general to say when things 'actually happen'. Time itself is very peculiar indeed in quantum physics!

Quantum mechanics has given us a picture of atomic structure, and explained spectral emissions and chemical bonding processes. Most importantly, it has led to an almost complete picture of the fundamental forces and particles of nature. Let's take a look at these now.

NOVEL CHALLENGE

In 2002, Brisbane student John Prior put a piece of photographic paper in a microwave oven and turned it on high. He knew that microwaves have a longer wavelength than infrared but nothing happened. Are you surprised to hear of his findings? Explain.

29.5 THE STANDARD MODEL

Fundamental forces

We have so far in this book recognised two fundamental forces of nature. We've examined mathematically both the gravitational and electromagnetic forces and understood that they both act over large distances and obey inverse square laws with distance. (See Table 29.2.)

The gravitational force keeps planets in orbit, controls the expansion of the universe and stops us from falling off the Earth into space. The electromagnetic force holds electrons in their atoms and binds matter together as molecules. Four forces in total are required to completely describe the universe around us, and in this section we look more closely at the interactions of the other two fundamental forces called the **strong interaction** or strong nuclear force and the **weak interaction** or weak nuclear force.

Table 29.2 FOUR FUNDAMENTAL FORCES

FORCE	EFFECTS	RELATIVE STRENGTH	RANGE
Gravitational	all interactions	1×10^{-38}	large distances inverse square
Electromagnetic	charged particle interactions	1×10^{-2}	large distances inverse square
Weak nuclear	weak interactions e.g. beta decay	1×10^{-13}	to 1×10^{-18} m
Strong nuclear	strong interactions e.g. nucleon bonds	1.0 (reference)	to 1×10^{-15} m

Hadrons and leptons

The strong interaction occurs within a class of particles called **hadrons**, of which the proton and the neutron are the best examples. The strong nuclear force is responsible for keeping protons and neutrons together in stable nuclei, despite the very obvious electrostatic repulsion that also occurs and the extremely high nuclear density. In a typical atomic nucleus the density of matter is about a billion tonnes per cubic centimetre. The only other place in the universe that such high matter density occurs is within pulsars and neutron stars. The strong nuclear force does not depend on electric charge and, within the confines of the nucleus, has the peculiar property of increasing in strength as the particle separation increases.

The weak interaction occurs between members of a class of particles called **leptons**, of which the electron is the best example. Weak interactions may also occur between lepton and hadron particles and are also independent of electric charge. The weak nuclear force is primarily responsible for slow nuclear processes such as radioactive decay of atoms and seems to control the energy-producing fusion reactions going on in stars. Physicists have also surmised that this force played a vital role in the building up of heavy elements from light nuclei in the early stages of formation of the universe. A typical strong-force interaction takes a trillion trillionth of a second whereas a typical weak-force interaction, such as the decay of a neutron, takes about fifteen minutes.

All knowledge of these nuclear forces has come from high energy physics using very powerful particle accelerator machines. These accelerators have also given us knowledge of the basic particles from which all matter is composed. Today, high energy particle theorists refer to a **standard model**, which summarises the known constituents of matter as well as the interactions between them. Table 29.3, as well as the diagram of Figure 29.13, portrays the links between these force interactions and fundamental particles. Before looking at the nature of these fundamental particles, let us complete the story of the force interactions.

The standard model consists of two parts, a part that is used to explain the weak nuclear interactions, called the **electroweak theory**, and a second part used to explain the strong nuclear interactions, called **quantum chromodynamics**, or QCD. Both parts are historically based on an earlier theory called **quantum electrodynamics**, or QED, which was formulated by Richard Feynman, Julian Schwinger and Sin-itiro Tomonaga in the late 1940s. QED theory explains the hydrogen atom as being stable because the proton and electron are continuously exchanging a photon particle between themselves. It's like two tennis players being considered as connected together while they are hitting the ball backward and forward. The photon is called a gauge **boson** particle and acts as the force carrier providing attraction. QED is called a relativistic quantum theory and was one of the first attempts at combining Planck–Bohr quantum theory with Einsteinian relativity.

Table 29.3 THE STANDARD MODEL

Matter: $m_e = 9.1 \times 10^{-31}$ kg

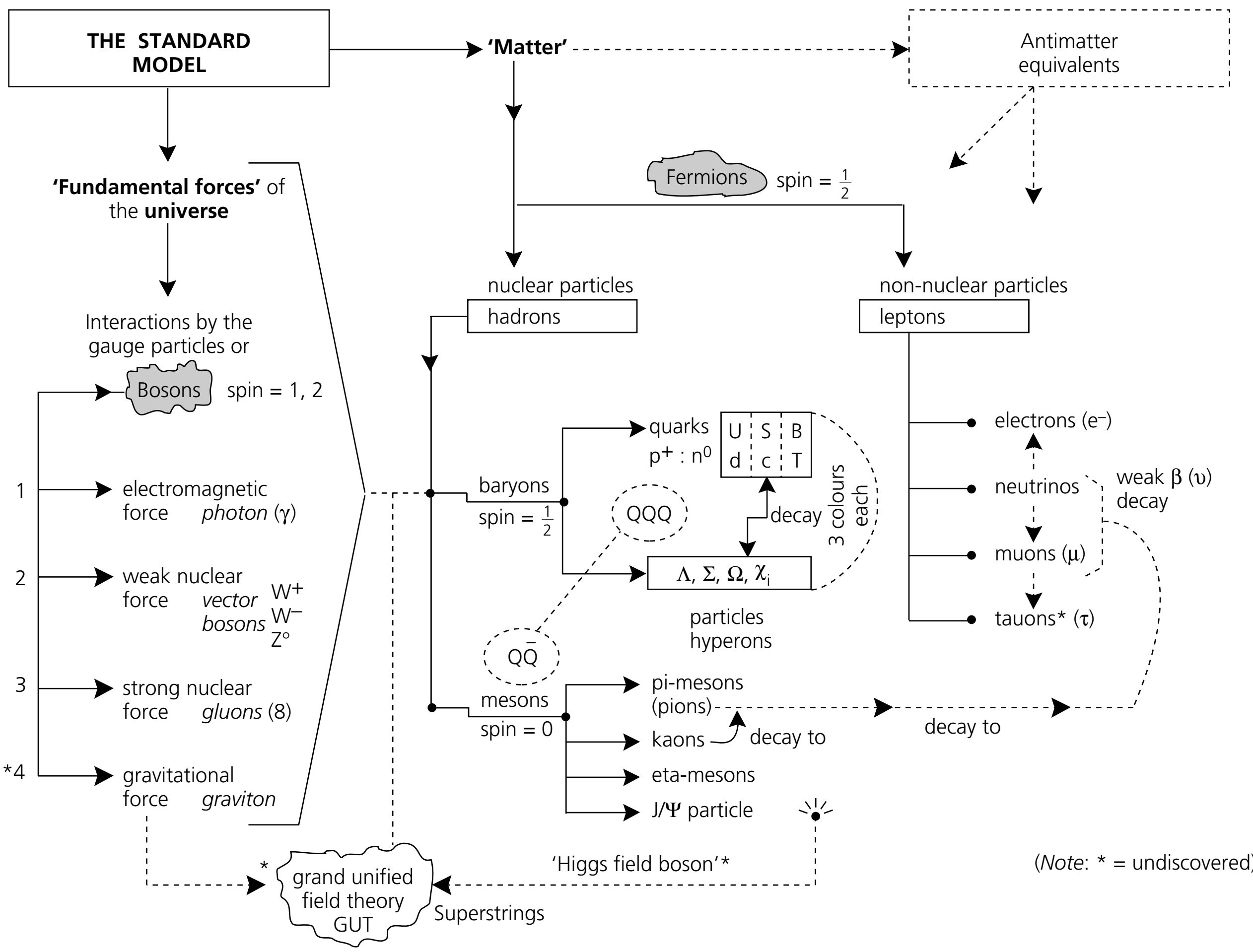
	First generation Normal matter Symbol	Charge	Mass	Second generation Symbol	Charge	Mass	Third generation Symbol	Charge	Mass
6 QUARKS	Up (u)	+2/3	610 m_e	Charmed (c)	+2/3	2900 m_e	Bottom (b)	+2/3	9800 m_e
	Down (d)	−1/3	610 m_e	Strange (s)	−1/3	300 m_e	Top (t)	−1/3	44 000 m_e
6 LEPTONS	Electron neutrino (ν_e)	0	≅ 0	Muon neutrino (ν_μ)	0	< 0.5 m_e	Tauon neutrino (ν_τ)	0	< 68 m_e
	Electron (e)	−1	m_e	Muon (μ)	−1	207 m_e	Tauon (τ)	−1	3491 m_e

GAUGE BOSONS ← Act on ← Force interaction

GAUGE BOSONS	Act on	Force interaction
8 Gluons	Nucleons and quarks	Strong nuclear
Intermediate vector Bosons W^+ W^- Z^0	Leptons	Weak nuclear
Photons (γ)	Nucleons and leptons	Electromagnetic
Gravitons *	All particles	Gravitational

* = Not yet discovered

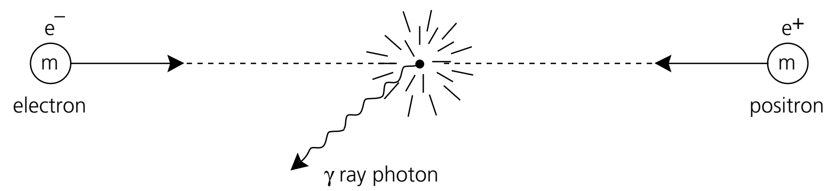
Figure 29.13
Overview of the 'standard model'.



In 1979, the Nobel physics prize was awarded to Steven Weinberg, Abdus Salam and Sheldon Lee Glashow for their work in applying QED to the electroweak theory. In the weak nuclear interaction of radioactive decay, a neutron effectively decays into a proton, an electron and an almost massless neutral particle called an **antineutrino**. The force that leads to the decay of a neutron is very weak. The electroweak theory explains this interaction or breakdown in terms of exchange particles called **intermediate vector bosons** designated as the W^+, W^- and Z^0 particles. These particles are very heavy and were not discovered until 1983 at CERN in Geneva.

The antineutrino involved in weak nuclear decay is characteristic of a complete range of antimatter particles that are now known to exist. In fact, every particle in physics has its own antiparticle, with the same mass but opposite electrical charge. **Antimatter** is very scarce in the universe generally because it has all been annihilated by normal matter during the early formation stages of the universe. (See Figure 29.14.)

Figure 29.14
Particle–antiparticle annihilation.



The second part of the standard model, called quantum chromodynamics (QCD), attempts to account for the behaviour of theoretical particles, called **quarks** and **gluons**, in forming elementary hadron particles such as protons and neutrons. Again, the theory suggests that the strong nuclear force holding neutrons and protons together is due to the exchange of a force-carrying boson, the gluon, between constituent quarks. The standard model allows for eight gluons and six quarks, although each quark has an associated mathematical property called **colour** charge. The word 'chromo' means colour. An analogy to this is the way that spectral colours can combine to produce light without colour, that is, white. Refer again to Table 29.3 and Figure 29.13.

Fundamental particles

All matter can be considered as divisible into the three major classifications of the standard model, namely **leptons**, **hadrons** and **bosons**. The bosons are unique in that they are their own antiparticles. They are force carriers between other particles. The best known is the electromagnetic photon, while the proposed graviton is yet to be discovered.

The lepton particles are involved in weak interactions as well as electromagnetic and gravitational interactions. The group includes electrons, **muons** and **neutrinos** and are particles that mathematically have spin of 1/2. Quantum theory prescribes that spin angular momentum can only occur in certain discrete values. These discrete values are described in terms of integer or half-integer multiples of the fundamental angular momentum unit, $h/2\pi$, where h is Planck's constant. In general usage, stating that a particle has spin 1/2 means that its spin angular momentum is $1/2\ (h/2\pi)$. Electrons and muons are electrically negative, while the neutrinos are neutral. The six lepton particles occur in 'Flavour' pairs as the:

- electron and the electron neutrino
- muon and the muon neutrino
- tauon and the tauon neutrino.

The word lepton comes from the Greek *leptos* meaning 'small and fine', although the tauon neutrino is nearly 68 times the mass of an electron.

Neutrinos are the most mysterious of the known elementary particles. They were postulated to exist by Wolfgang Pauli in the 1930s, when they were necessary to conserve conservation laws in radioactive β decay. Pauli called them neutrinos, meaning 'little neutral ones'. In 1956 the neutrino was verified in experiments at the Savannah River reactor in the USA by physicists Fred Reines and Clyde Cowan Jr. Because the neutrinos have no charge and

MASSIVE NEUTRINOS

On 5 June 1998, at the Neutrino-98 physics conference at Takayama, Japan, it was announced that the Japanese and American Super-Kamiokande experimental group had detected evidence for the non-zero mass of neutrinos. By studying neutrino interactions in a 50 000 tonne underground tank of purified water, the group had concluded that neutrinos were oscillating between types as they interacted with the water and produced faint light pulses. This would only be possible if they actually had mass. The team concluded that the missing universe dark matter may now be associated with neutrinos.

NOVEL CHALLENGE

A columnist in *The Times* (London) newspaper on 11 October 1996 asked: 'What use are quarks; can you eat them?' The distinguished Cambridge metallurgist Sir Alan Cottrell replied, 'I estimate that he eats 500 000 000 000 000 000 000 000 001 each day.' Was Sir Alan correct? Make some rough estimates about food intake and derive your own amount. *Hint:* the mass of a proton or a neutron is 1.67×10^{-27} kg.

negligible mass, they can only be observed by measuring their momentum recoil effects on other particles. They interact very weakly with matter. It has been estimated that solar neutrinos will pass through about 100 light years of water before losing energy. They have no trouble passing through the Earth, for instance. The Sun is a powerful source of natural neutrinos providing an electron neutrino flux density at the Earth's surface of about 6.6×10^{10} cm^{-2} s^{-1}. Let's face it, you are always being literally blasted with neutrinos. It's just as well they appear to do no harm.

The hadron particles may undergo strong nuclear interactions and are subdivided into two classes called **mesons** and **baryons**. Sometimes they may be referred to as nucleons. The most interesting feature of hadrons is that they can be broken down into even more fundamental particles called quarks. Separate quarks do not exist but mesons are quark–antiquark pairs, while baryons are made of three-quark combinations. (See Figure 29.15.)

The mesons have mathematical spin of 0 and are electrically charged, either positive, negative or neutral. Most have masses somewhere between the proton and the electron. Meson comes from the Greek *mesos* meaning 'middle'. They are very short-lived particles. For example, the neutral pion may only last for about 1×10^{-16} s and will decay into leptons.

The baryons have mathematical spin of 1/2. The commonest are the proton and the neutron, with many being more massive than either of these. Baryon comes from the Greek *barus* meaning 'heavy'. The proton is stable and lasts indefinitely, while a free neutron decays in about 15 minutes into a proton, an electron and an antineutrino. Most larger baryons, called **hyperons**, decay into protons and neutrons.

In the early 1960s, American physicists Murray Gell-Mann and George Zweig suggested that hadrons were composed of more fundamental particles called quarks. Gell-Mann coined the word from a phrase in James Joyce's *Finnigan's Wake*, 'three quarks for muster Mark'. These quarks, along with the leptons, constitute the true elementary particles of nature. This concept brought a simpler order to the multitude of particles that had been discovered. The symmetry of six quarks, six leptons and eight bosons was quite simple and allowed all other particles to be classified into the standard model that we have today.

The six quarks are the up, down, strange, charmed, bottom and top; whimsical names introduced to describe various mathematical properties within the theory of their behaviour. An interesting story surrounds the naming of the 'strange' quark. When kaon particles were first discovered in 1947 as a result of cloud chamber studies of cosmic rays, they were noted to do something peculiar with time. Kaons can be created extremely quickly in about one trillion trillionth of a second by colliding protons and neutrons, but once formed they take a considerably longer time of about one nanosecond to decay into pions. This seems to violate the law of time symmetry and reversibility of fundamental physical processes, which generally require formation and decay processes to be opposites. This strange behaviour was subsequently called 'strangeness' when also noted for several other particles. Today, it is known that strangeness is due to the presence of a strange–antistrange quark pair and the decay processes of kaons involve the weak nuclear force in such a way that the time reversibility laws are not violated.

The quark proportional electric charges and masses are tabulated in Table 29.3. For example, a neutron particle contains an up quark, u, and two down quarks, d:

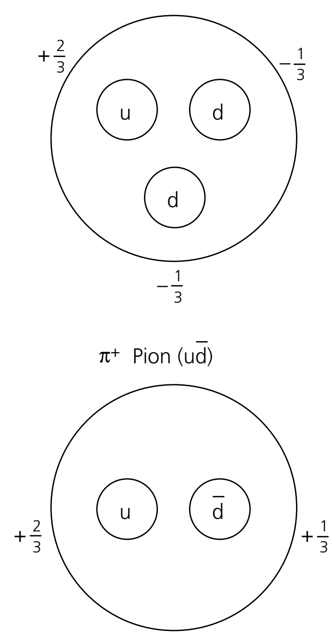
$$\text{neutron (n) udd} = +\frac{2}{3} - \frac{1}{3} - \frac{1}{3} = 0 \text{ or neutral charge}$$

while a positive pion particle contains an up quark, u, and an antidown quark, $\bar{d}$:

$$\text{pion } (\pi^+)\ u\bar{d} = +\frac{2}{3} + \frac{1}{3} = +1 \text{ or positive charge}$$

The last quark to be discovered, the top quark, was reported only in 1995 from an international team working at FERMILAB, near Chicago, USA.

Figure 29.15
Quark structure of a neutron and a pi-meson.



PHYSICS UPDATE

An international team of physicists has made a batch of 'strange' particles in experiments that could further our understanding of the universe and help with the understanding of collapsed stars called neutron stars, which are thought to contain them.

In 2001, the team created atomic nuclei containing two strange quarks at the Brookhaven National Laboratory in the United States. Since the 1960s only a handful of such particles have been detected and then only in small quantities; but the Brookhaven team of specialists said, 'This is the first experiment to produce large numbers of these doubly strange nuclei'.

The experiment took place within a particle accelerator, where atoms were smashed into their constituent particles, the building blocks of matter producing significant numbers of nuclei containing two strange quarks. (Out of 100 million collisions, 30–40 examples of the doubly strange objects were found).

Normal everyday matter around us consists entirely of only four particles — the electron, the electron neutrino, the up quark and the down quark. These particles are what you consumed for lunch, for instance, so next time someone asks you what you had to eat, tell them! The second generation of particles, the muon, the muon neutrino and the charmed and the strange quarks, are found only in accelerator experiments and in cosmic rays. The third generation particles, discovered since the mid-1970s in very high energy particle accelerators, are thought to describe the state of matter in the early formation stages of the universe.

The dark matter problem

Physicists who study the evolution of the universe (called cosmologists) have calculated that there is a critical density that will determine whether the universe will collapse under its own gravitational attraction (a 'closed' universe) or continue to expand as it currently does (an 'open' universe). When they began looking at the total amount of mass existing in the universe they defined a quantity called omega (Ω). This is the ratio of the measured density of the universe divided by the critical density required for collapse. If omega is greater than 1.0 then the total amount of matter in the universe will eventually cause it to collapse. If omega is less than 1.0 then the universe will continue to expand as it currently does forever. Cosmologists have evidence to suggest that the universe is currently in a state of inflationary balance which suggests that omega equals 1.0.

In actual observations and measurements, modern cosmologists have come across a big problem — the amount of visible matter in the universe produces an omega equal to 0.05 or thereabouts. This means that there is about 95% of the total necessary mass of the universe that is missing! The missing mass has come to be known as '**dark matter**'. A bigger problem is that there also doesn't seem to be enough mass in the observable universe to account for the predictions made by a very successful theory called 'big bang nucleosynthesis' or BBN. This is the current theory which correctly predicts the amounts of hydrogen and helium in the universe and gives the methods for forming larger elements from baryons. If BBN is correct, then the original amount of baryonic matter formed in the Big Bang was about omega = 0.1. So the big question in modern cosmology is: 'What constitutes the universe's missing dark matter?'

Several candidates are being investigated apart from the types of matter that are not easily observable, such as other planets, dim stars, brown dwarfs and exotic particles. The most important of these are the neutrinos which, even if they have a very small mass of about 90 eV, are so numerous as to almost completely account for the missing dark matter. If the universe dark matter is mostly neutrinos, or similar particles, then the dark matter will be termed 'hot dark matter — **HDM**' as the particles are very light, move very fast and will help form large scale structures such as walls, filaments and strings.

The universe dark matter may also be made up of **WIMPS** or 'weakly interacting massive particles' — so called because they are assumed to be extremely massive particles (about 10–100 times the mass of a proton) that do not interact with normal matter very strongly. These particles feel only gravity and the weak nuclear force; and they are impervious to the strong nuclear force and the electromagnetic force (hence we haven't discovered them yet). Such heavy particles would be slow-moving and are known as 'cold dark matter — **CDM**'. This form of dark matter will have assisted in the formation of smaller structures such as galaxies.

Dark matter may in fact it be a mixture of CDM and HDM called 'mixed dark matter — **MDM**'. Cosmologists believe that as the universe grows older, dark matter will become the dominant energy-generation mechanism for the entire universe. Whatever is discovered in the future, dark matter obviously has a lot to do with the way the universe works, and is responsible for the way that the universe is structured.

29.6 THE FUTURE

Beam me up, Scotty!

Australian engineers and physicists are at the forefront of quantum technology. Collaboration between research staff members at the Australian Research Centre (ARC) Quantum Computer Technology facility at the University of Queensland and the Australian National University are at the cutting edge in developing the next generation of computer technology called **quantum computers**, which use particles of light (photons) and fibre optics rather than silicon chip conduction.

Current computer technology is thought to be heading for a 'brick-wall' barrier due to physical semiconductor size constraints and IC chip production costs around the year 2010. Quantum computers will provide a means of overcoming this barrier, by building computers at the level of single electrons and atoms, using principles of quantum physics rather than semiconductor physics and electronics. This technology will dramatically increase the speed and quantity of digital information that can be transmitted over fibre-optic cables. At the heart of the process is the technique of '**teleportation**' which means breaking down an object at one location and reconstructing it at a completely different location. This brings to mind the line 'Beam me up, Scotty' in the famous *Star Trek* series. The researchers have demonstrated models for the teleportation of photons, which is the first step. Teleportation is not only necessary for quantum computing but will also have applications in general communications and security encryption techniques for data (cryptography).

You can see that quantum theory and particle physics have been very intense areas of research since the 1920s. It is remarkable that for physicists and **cosmologists** to understand the universe it is necessary to understand the smallest elementary particles. This is because the elementary particles were formed in the first fragments of time following the Big Bang. In fact, time itself only has meaning following the Big Bang! Understanding how these elementary particles form and interact gives insights into how the universe has evolved and where it is going. Eminent cosmologist Stephen Hawking, who became the Lucasian Professor of Mathematics at the University of Cambridge in 1979, has spent most of his life theorising about the universe, elementary particles and black holes. Hawking's theory combines general relativity and quantum theory into quantum gravity, in which he regards the universe as an expanding entity in which space and time form a closed surface without boundaries. Hawking's cosmology ideas relating to the history of time and the universe have been some of the most important since the original Einstein field equations of general relativity and Edwin Hubble's discovery of the expanding universe. You may have seen Professor Hawking on television speaking through a voice computer and confined to an electric wheelchair.

Today, with data from the cosmic background explorer satellite (COBE) and the Hubble space telescope, physicists are beginning to gain knowledge and understanding about the probable age and fate of the universe. The importance of particle physics to cosmology was in evidence during the famous 1987 A supernova explosion. This was the first exploding star visible to the naked eye for 384 years. Three hours before it was observed with telescopes, two separate underground particle detectors in Painesville, Ohio, USA and Kamioka, Japan detected an influx of neutrino particles that were later analysed.

In physics, a so-called **theory of everything**, or TOE, would provide a complete description of all the forces and particles of nature. In other words, it would contain all parts of the standard model described earlier. It might also explain why the laws of physics are the way they are! It is this question of 'why?' that is so important and not just a description of 'what?'! **Grand unified theories** or GUTs will unify the gravitational, electroweak and strong

PHYSICS UPDATE

Two international teams of astronomers, using NASA's Hubble Space Telescope and ground-based telescopes in Australia and Chile, have discovered the first examples of isolated stellar-mass black holes adrift among the stars in our galaxy.

All previously known stellar black holes have been found in orbit around normal stars, with their presence determined by their effect on the companion star. The two isolated black holes were detected indirectly by the way their extreme gravity bends the light of a more distant star behind them. 'These results suggest that black holes are common and that many massive but normal stars may end their lives as black holes instead of neutron stars,' said David Bennett of the University of Notre Dame.

It has been confirmed recently that a supermassive black hole exists at the centre of our Milky Way galaxy. The black hole has a mass of 3.7 ± 1.5 million solar masses, and the discovery team now believes that a supermassive black hole exists at the centre of every galaxy.

interactions of nature. All this cosmology research is mathematically complex, but there are numerous general interest books available on the subject that give the ideas without the maths. Try to find some!

High energy particle physics is looking forward to 2007 when the exciting large hadron collider (LHC) machine is due to come online at CERN. The LHC will produce head-on collisions between pairs of protons with energies of about 8.0 TeV. Australian research groups are already part of the many projects planned. It is expected that the LHC machine will have enough energy to be able to confirm the existence of the Higgs field boson particle, important in the standard model of matter because it produces spontaneous symmetry breaking and 'allows' normal particles to have mass. Even further into the future, high energy particle physicists are expecting to produce electron-positron colliders to complement the LHC. These machines will really begin to answer 'What next?' type questions.

Questions

11 Calculate the de Broglie wavelength of an electron travelling at 7.5×10^5 m s^{-1} in a cathode ray tube.

12 How does the notion of electron position probability allow us to view the modern atom?

13 Under what conditions is the Heisenberg uncertainty principle important?

14 Explain the differences between leptons, hadrons and bosons.

15 Make notes on the important contribution made to quantum mechanical theory by the following physicists: Wolfgang Pauli, Erwin Schrödinger, Richard Feynman, Murray Gell-Mann, Stephen Hawking.

Practice questions

The relative difficulty of these questions is indicated by the number of stars beside each question number: * = low; ** = medium; *** = high.

Review — applying principles and problem solving

***16** Give two reasons why Compton scattering provides evidence that supports a particle model for photons.

***17** What is the energy in both joules and electronvolts of a photon whose wavelength is 5.5×10^{-7} m?

***18** The threshold frequency for a particular metal is 2.5×10^{14} Hz. If light of frequency 6.0×10^{14} Hz falls onto the surface, calculate **(a)** the colour of the incident light; **(b)** the incident photon energy; **(c)** the metal's work function; **(d)** the maximum kinetic energy of the photoelectrons; **(e)** the maximum velocity of the photoelectrons.

***19** Calculate the de Broglie wavelength of an electron travelling at 80% the speed of light. Compare this with the diameter of a hydrogen atom.

****20** Use the hydrogen energy level diagram in Figure 29.6 to answer the following:

(a) How much energy must be supplied to raise the atom from quantum state $n = 1$ to $n = 4$?

(b) How much energy is needed to ionise the atom?

(c) What is the frequency of the photon emitted in an electron transition from $n = 5$ to $n = 1$?

***21** Use Einstein's famous equation $E = mc^2$ to determine the energy released when an electron annihilates a positron, each of mass 9.11×10^{-31} kg.

***22** Name the general types of particles that are influenced by the interactions of **(a)** the weak nuclear force; **(b)** the strong nuclear force; **(c)** the gravitational force.

***23** In the quark theory, a normal proton is described as a uud particle. Describe what this means and prove that its electric charge is +1.

***24** Why is the standard model currently regarded as a very good description of the fundamental interactions of nature?

****25** Table 29.4 contains data obtained from a photoelectric experiment. By graphing $E_{K(max)}$ versus frequency, use these data to obtain values for:
(a) Planck's constant in electronvolts; **(b)** the threshold frequency for the metal; **(c)** the work function of the metal.

Table 29.4

$E_{K(max)}$ (eV)	0.5	0.8	1.2	1.75	2.3	2.5
$f(\times 10^{14})$ (Hz)	3.75	4.5	5.5	7.0	8.0	8.9

****26** Produce a quantum mechanical argument as to why it is easier to predict the path of a more massive object, such as a bicycle, rather than a very small object, such as an alpha particle.

****27** The energies of possible quantum states for a gas are listed below. Reorganise these data and represent them on an appropriate energy level diagram. Assume that the ground state energy has been included. Use the diagram to answer the questions that follow:

-8.64×10^{-19} J -5.76×10^{-19} J -16.6×10^{-19} J
-11.5×10^{-19} J -6.72×10^{-19} J

(a) What is the shortest and longest wavelength expected in the emission spectra of this gas under excitation?
(b) How much energy is required to cause the gas atoms to change from energy level 3 to energy level 4?

Extension — complex, challenging and novel

*****28** It is found that a neutron travelling at 1.98×10^4 m s^{-1} has the same energy as a light photon of frequency 5×10^{14} Hz. What is the mass of the neutron?

*****29** In an experiment similar to that of Franck and Hertz, electrons of energy 12 eV are fired into a gas. Electrons penetrating the gas are collected and their energies measured at 12 eV, 1.4 eV and x eV. If the spectrum of the light emitted from the gas is also analysed and found to contain photon energies of 11.4 eV, 10.6 eV and y eV, deduce the values of x and y.

*****30** Calculate the de Broglie wavelength of an electron in a cathode ray tube that uses a gun accelerating potential of 750 V.

*****31** The energy levels of a particular type of atom are as follows:

0.00×10^{-19} J 3.36×10^{-19} J 4.96×10^{-19} J
5.76×10^{-19} J 5.92×10^{-19} J 8.16×10^{-19} J.

(a) If atoms in the ground state are bombarded with electrons, what is the minimum energy required to detach an electron from the atom?
(b) If the atoms are bombarded with electrons of energy 5.28×10^{-19} J, what will be the photon energies emitted?
(c) What will be the maximum energy of the scattered electron if a 1.60×10^{-19} J photon is produced in the collision of a 5.58×10^{-19} J bombarding electron with this atom?

*****32** Propose a reason for a head-on collision of two beams of 1 GeV protons being more useful to physicists studying high levels of energy than the collision of a single beam of 2 GeV protons with a fixed target.

*****33** In 1993, the United States Congress voted to stop funding one of the largest particle accelerator projects ever conceived. It was the 20 TeV superconducting supercollider (SSC) to be completed in an 87 km circumference tunnel near Waxahachie, Texas. The reason for the project's abandonment was its projected cost of over $US10 billion. Try to list arguments for why this type of project has both advantages to science and disadvantages to society. How would you vote if you had the chance?

****34** **Max Planck and the 'Deutsche Physik'** The following extract has been taken from the book *Heisenberg probably slept here* by Richard Brennan and published by John Wiley & Sons, NY, 1997. It is the story of Max Planck, one of the most famous German scientists who ever lived. He has been mentioned in this chapter for his discoveries, especially the quantum nature of heat radiation.

Unlike Einstein, Max Planck was caught up in the patriotic frenzy in Germany before the First World War and fully supported Germany's position in what he believed to be a defensive and inevitable war against evil opponents. Planck was the father of two boys of military age and the rector of a university soon to be depopulated by the calling up for military service of both students and the younger instructors. Soon Planck's children were all involved in the war. His girls, Greta and Emma, had trained with the Red Cross and were awaiting assignment to military hospitals. Planck's oldest son, Karl, was at artillery school, and his youngest son, Erwin, was already at the front. 'What a glorious time we are living in', Planck wrote to his sister. 'It is a great feeling to be able to call oneself a German.' How the Plancks ever tolerated their friend Einstein passing out antiwar propaganda on street corners is a mystery. Possibly they considered him a hopeless eccentric. By 1915, the horrors of the First World War became personal for Planck. His nephew, a physicist, his brother's only son, was killed. His own son Erwin had been taken prisoner, and Karl was injured and died of his wounds.

In late 1917 defeat was in the air and the German government was near collapse. But even given all of the tragedy visited on his family and the imminent defeat, Planck refused to sign a proclamation calling for the resignation of the Kaiser, as Einstein had. He was loyal to the end. Despite political differences, Planck's relationship with Einstein remained cordial.

Continuing family tragedies caused Planck great grief. In 1917, his daughter Greta died suddenly a week after giving birth. Her twin sister, Emma, came to Heidelberg to care for the infant, and in 1919 married the widower. By that year's end she too was to die shortly after giving birth. This double tragedy almost destroyed Max Planck. 'There are times now', he wrote, 'when I doubt the value of life itself.'

Planck found solace from public and domestic tragedy both in his work and in helping to raise his grandchildren. His quantum principles were becoming more and more acceptable in the world of science and had expanded into virtually every area of physics. Planck's theorised constant h *came to be regarded as a fundamental constant of nature, the equal of Einstein's* c*, the velocity of light.*

The Nazis and 'Deutsche Physik'

The next period of special note in Planck's life started at the dawn of the Nazi era. In 1930, Planck became president of the Kaiser Wilhelm Society of Berlin, which was then renamed the Max Planck Society. In his seventies at the time, Planck's renown in the world of science was second only to that of Einstein.

The days of Nazi ascendancy in Germany were difficult both for science and for Max Planck personally. The issues were Einstein, because he was a Jew, and the theories of relativity and quantum physics. Anti-Semites (anti-Jews) identified relativity and quantum theories as the decadent work of Jews. In contrast, the right wing extolled the virtues of applied physics, called 'Deutsche Physik', as opposed to contaminated theoretical or Jewish physics. Many German scientists lined up on the Nazi side, and Planck found himself drawn into this ugly fight. The position he took was ambivalent. On the one hand, the major prestigious scientific societies of which he was a leading member remained silent and did not come to Einstein's defense. Privately Planck condemned the Nazi attacks on Einstein as 'scarcely believable filth'. Publicly he tried to stay out of what he called 'political issues'. On the other hand, Planck vigorously defended the theories of relativity. As president of the Society of German Scientists and Physicians, Planck proposed that Einstein be invited to address the annual meeting. Planck hoped that the irrefutable logic of Einstein's science could win the day. Einstein at first accepted the challenge but was forced to withdraw after threats were made on his life. Planck was fighting a losing battle to separate ivory tower science from street politics.

In January of 1933, Adolph Hitler became Reich chancellor and the Nazis were in full power. Max Planck was secretary of the Academy of Science and president of the Kaiser Wilhelm Society, key positions in the scientific establishment in two organisations that depended on the government for financial support. Planck was faced with the choice of either resigning and leaving the country or staying and attempting to moderate Nazi policies. He chose the latter. His hope was to cause compromises for the sake of science, but compromise was not to be had.

Einstein by this time had decided to emigrate to the United States. Letters between the two physicists revealed their separate states of mind with regard to the advisability of compromise with the Nazis, and they would eventually split on this issue. Planck fought long and hard to protect his Jewish students and colleagues, but in the end his efforts could do no more than delay their persecution. Although he never lent his voice and prestige to the Nazi regime in any way, he never stood up firmly or publicly against it. When the Nazis barred all Jewish faculty and students from the universities and Planck remained silent, Einstein broke off their long relationship and never spoke to him again.

Despite the fact that Planck never publicly opposed the Nazi regime, the regime had mixed feelings about Planck. On the one hand, he was a world-renowned scientist, and he and his fame were used in Nazi propaganda efforts. On the other hand, he continued to espouse relativity (even though he ceased using Einstein's name in connection with the theories). This was a typical Planck compromise, for which his reputation suffered abroad. On Planck's eightieth birthday Hitler sent him good wishes, while at the same time Nazi minister for propaganda Joseph Goebbels was trying to prove that he was one-sixteenth Jewish and therefore not fit to lead German science.

Late in 1944, Max Planck's last living child, his beloved son Erwin, was arrested in connection with the plot to kill Hitler. A Nazi court quickly found him guilty, and he was condemned to death. Planck used every political means at his command to save his son. According to one account of what followed, a high Nazi official contacted Planck with a proposed bargain:

Planck would at last join the Nazi party, adding his still-considerable international prestige to their cause. In appreciation, Planck was told, they would seek to commute Erwin's sentence to a prison term. The old man refused. On 23 February 1945, Erwin was executed. Planck was devastated by this loss. To a niece and nephew he wrote, 'He was a precious part of my being. He was my sunshine, my pride, my hope. No words can described what I have lost with him.'

SR

Question: Jewish physics and 'Deutsche Physik' were labels applied by the Nazis to two scientific viewpoints current in Germany in the 1940s. Which one did Planck support and what factors contributed to his position? Was he correct? Support your argument by comparing and contrasting the two types of German science referred to in the article above.

****35** Read the following, about strange new particles, and answer the question that follows.

The tremendous energies available in cosmic rays and particle accelerators led to the discovery of large numbers of additional particles such as kaons and mesons, but also some exotic ones which were referred to as 'strange' particles. Whereas once physicists had only three nuclear particles to deal with, they now had a bewildering array of new particles with a great variety of charges, spins, masses and quantum numbers. There was not the simplicity they had come to expect, so a new theory was needed.

Quarks

A ray of hope came along in the early 1960s with Murray Gell-Mann and George Zweig, who proposed independently that the many hadrons (i.e. baryons and mesons) consisted of smaller particles, which became known as quarks (from James Joyce's novel *Finnegan's Wake*). The quarks, along with the photon and the leptons, would be the true elementary particles.

Three different types of quark were suggested, called 'up' (u), 'down' (d) and 'strange' (s). Later it was found that three more were required; these were known as 'charm' (c), 'top' (t) and 'bottom' (b). All six have antiparticles. Four of the quarks, with some of their properties, are listed in the table below. For charge to work out correctly quarks must all have fractional charges of either

$\pm\frac{2}{3}$ or $\pm\frac{1}{3}$.

A baryon is made up of three quarks and a meson is made up of one quark and one antiquark.

TYPE OF QUARK	SYMBOL	CHARGE	STRANGENESS
up	u	$+\frac{2}{3}e$	0
down	d	$-\frac{1}{3}e$	0
strange	s	$-\frac{1}{3}e$	−1
antistrange	$\bar{s}$	$+\frac{1}{3}e$	+1

Adapted from *Advanced Physics*, J. Murray, 4th Edition by Tom Duncan (1994)

Question: Use the information above to determine the quark structure of each of the fundamental particles in Table 29.5, given that each is composed of two or three quarks. Show all reasoning.

Table 29.5

PARTICLE	SYMBOL	CHARGE	STRANGENESS
pion +	π^+	+1	0
sigma –	Σ^-	–1	–1