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.

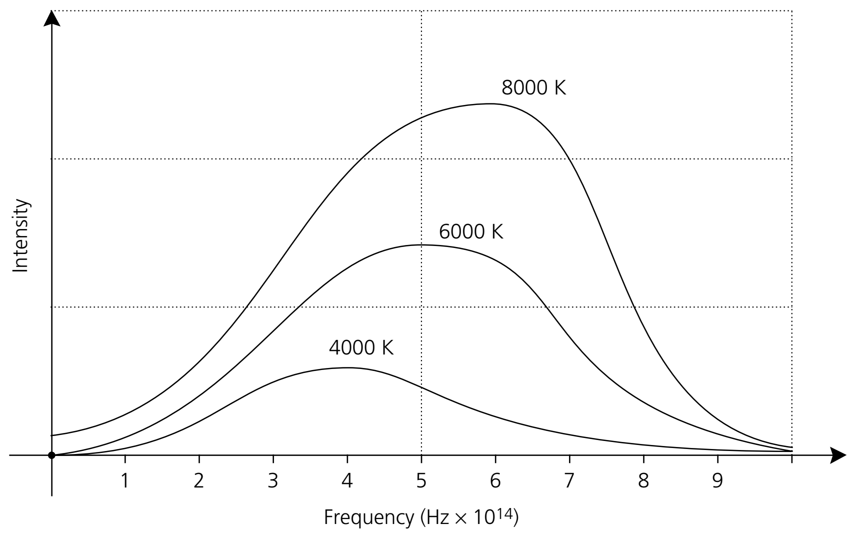


Figure 29.1
Black body radiation.

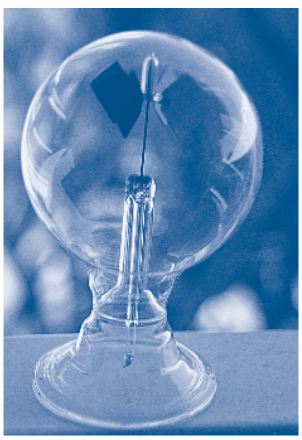


Photo 29.1
Crookes' radiometer with the black and white vanes clearly visible.

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.

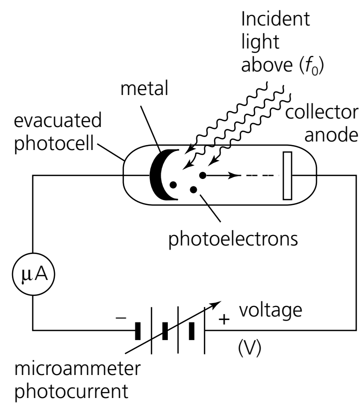
The photoelectric effect

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?