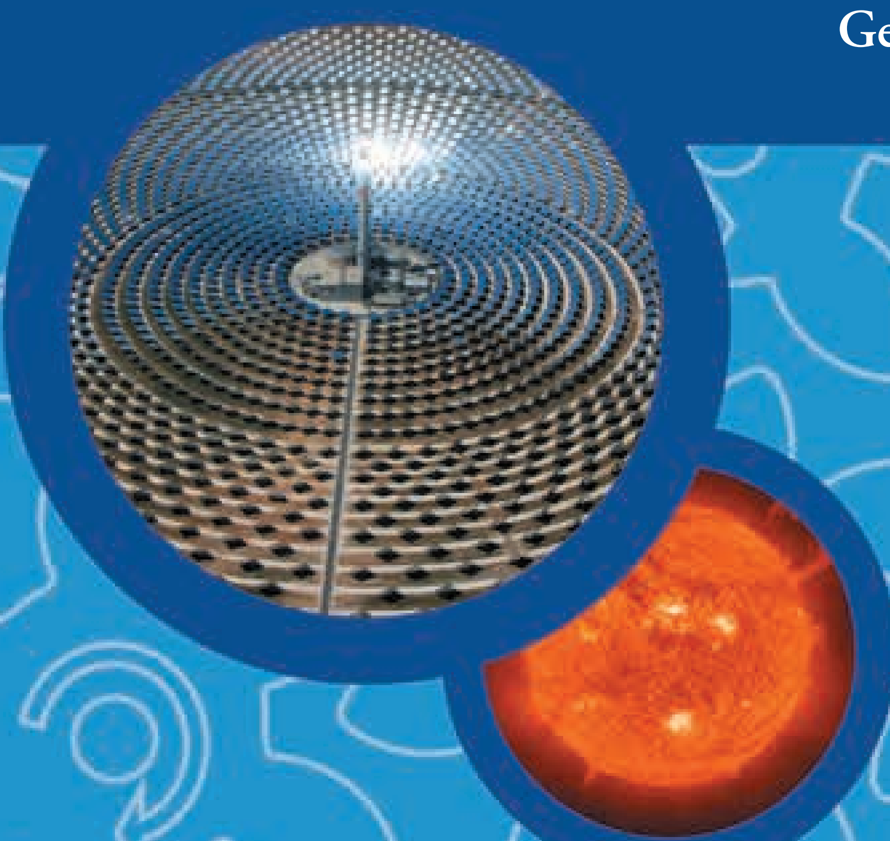
Physics of Energy Sources

George C. King



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Physics of Energy Sources

The Manchester Physics Series

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J.R. FORSHAW, H.F. GLEESON, F.K. LOEBINGER

School of Physics and Astronomy,
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Physics of Energy Sources

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‘But why are such terrific efforts made just to find new particles?’ asked Mr Tompkins.

‘Well, this is science,’ replied the professor, ‘the attempt of the human mind to understand everything around us, be it giant stellar galaxies, microscopic bacteria, or these elementary particles. It is interesting and exciting, and that is why we are doing it.’

From *Mr Tompkins Tastes a Japanese Meal,* by George Gamow (*Mr Tompkins in Paperback*, Cambridge University Press (1965), p.186).

To my family: Michele,
May, George and May.

Contents

Editors' preface to the Manchester Physics Series

The Manchester Physics Series is a set of textbooks at first degree level. It grew out of the experience at the University of Manchester, widely shared elsewhere, that many textbooks contain much more material than can be accommodated in a typical undergraduate course; and that this material is only rarely so arranged as to allow the definition of a short self-contained course. The plan for this series was to produce short books so that lecturers would find them attractive for undergraduate courses, and so that students would not be frightened off by their encyclopaedic size or price. To achieve this, we have been very selective in the choice of topics, with the emphasis on the basic physics together with some instructive, stimulating and useful applications.

Although these books were conceived as a series, each of them is self-contained and can be used independently of the others. Several of them are suitable for wider use in other sciences. Each Author's Preface gives details about the level, prerequisites, etc., of that volume.

The Manchester Physics Series has been very successful since its inception over 40 years ago, with total sales of more than a quarter of a million copies. We are extremely grateful to the many students and colleagues, at Manchester and elsewhere, for helpful criticisms and stimulating comments. Our particular thanks go to the authors for all the work they have done, for the many new ideas they have contributed, and for discussing patiently, and often accepting, the suggestions of the editors.

Finally we would like to thank our publishers, John Wiley & Sons, Ltd., for their enthusiastic and continued commitment to the Manchester Physics Series.

J. R. Forshaw
H. F. Gleeson
F. K. Loebinger
August 2014

Author's preface

We live in a technological age where energy plays a central role. Because of its importance, issues regarding the availability and cost of energy and the environmental impact are never far from the daily news. This book describes the main sources of energy that are available to us together with the underlying physics that governs them. In particular, it deals with nuclear power, solar power, wind power, wave and tidal power. The book also describes the ways in which energy can be stored for future use. Studying the physics of energy sources has various advantages. First, such a study encompasses a wide range of physics from classical physics to quantum physics. In this way it supports other undergraduate courses in the physical sciences and engineering. Secondly, energy sources represent real applications of fundamental physics, and although energy sources are being continuously developed, the underlying physics that governs them remains the same. The book is addressed mainly to science and engineering students, who require knowledge of the physical principles governing the operation of energy sources. It is based on an introductory 24-lecture course entitled "Physics of Energy Sources" given by the author at the University of Manchester. The course was attended by first- and second-year undergraduate students taking physics or a joint honours degree course with physics, but it should also be useful for students on engineering and environmental science degree courses. The book covers the topics given in the course although it amplifies the material delivered in the lectures. A basic knowledge of differentiation and integration is assumed and simple differential equations are used, while undue mathematical complication and detail are avoided.

The organisation of the book is as follows. Chapter 1 deals with energy consumption and outlines the main energy resources available to us and the physical characteristics of energy sources. The transformation of energy from one form to another is considered, together with the role of energy storage. Chapter 2 deals with the properties of the atomic nucleus, nuclear forces and radioactivity, and forms a foundation for the understanding of nuclear fission and nuclear fusion. These are dealt with in Chapter 3, which describes how we get energy from the nucleus, by both the fission of heavy nuclei and the fusion of light nuclei. Chapter 4 describes the origin and properties of solar radiation, its interaction with the Earth and how thermal energy can be harvested from sunlight. The conversion of thermal energy into mechanical energy is also discussed. Chapter 5 is devoted to semiconductor solar cells and includes a description of the band structure of semiconductors and the action of the p–n junction. Chapter 6 deals with the harnessing of wind power by wind turbines and introduces the elements of fluid mechanics. Chapter 7 describes water power in its various forms, including hydroelectric power, wave power and tidal power. This includes a discussion of wave motion and also the origin of the tides. Chapters 4, 5, 6 and 7 are thus about renewable energy sources. Finally, Chapter 8 describes various ways in which energy can be stored for future use. Fossil fuels are not dealt with explicitly. However, these fuels are usually used to produce thermal energy that drives steam turbines. In this respect, they have much in common with, for example nuclear power, where again the energy is first converted into thermal energy to drive steam turbines, and similar thermodynamic principles apply.

Worked examples are included in the text. In addition, each chapter is accompanied by a set of problems that form an important part of the book. These have been designed to deepen the understanding of the reader and develop their skill and self-confidence in the use of the physics. Hints and solutions to these problems are given at the end of the book. It is, of course, beneficial for the reader to try to solve the problems before consulting the solutions.

I am particularly indebted to Fred Loebinger who was my editor throughout the writing of the book. He read the manuscript with great care and physical insight and made numerous and valuable comments and suggestions. I am grateful to the members of the Manchester Physics Series Editorial Board – Fred Loebinger, Helen Gleeson, Jeff Forshaw and Jenny Cossham – for helpful suggestions regarding the content and organisation of the book. I am also grateful to my colleagues David Binks, Mark Dickinson and Jeff Forshaw for valuable and enlightening discussions about various topics in physics, and to Michele Siggel-King for constructing some of the figures.

George C. King
January 2017

1

Introduction

Energy is essential to our lives. Our bodies need energy to function and to perform physical activities. And the technological age in which we live needs a reliable energy supply for heating, lighting, communication, transport, food production, manufacturing goods, and so on. Because of their importance, issues such as the supply and cost of energy and the environmental impact make frequent appearances on the daily news. In this introductory chapter we consider energy consumption and the energy resources available to us. We consider the general characteristics of energy sources and the transformation of energy from one form to another to suit the end use. We also consider the role of energy storage.

1.1 Energy consumption

We consume energy in maintaining our vital bodily functions, such as the operation of the heart and lungs, the maintenance of body temperature, brain function and digestion of the food we eat. Roughly speaking, in maintaining these functions we consume energy at the rate of ~100 J/s; a power of ~100 W. We also expend energy when we do physical work. Suppose, for example, that we climb stairs and rise at the rate of 0.5 m/s in vertical height. If our mass is 75 kg, our rate of doing work is $75\,\mathrm{kg} \times 9.8\,\mathrm{m/s^2} \times 0.5\,\mathrm{m/s} = 368\,\mathrm{W}$. The amount of physical activity that a person does depends on their lifestyle. Suppose, however, that, averaged over the course of a 24-hour period, we consume energy at the average rate of 125 W in maintaining our metabolic rate and performing physical work. This amounts to ~10 MJ of energy per day. This energy comes from the chemical energy stored in the food that we eat; a tin of baked beans,

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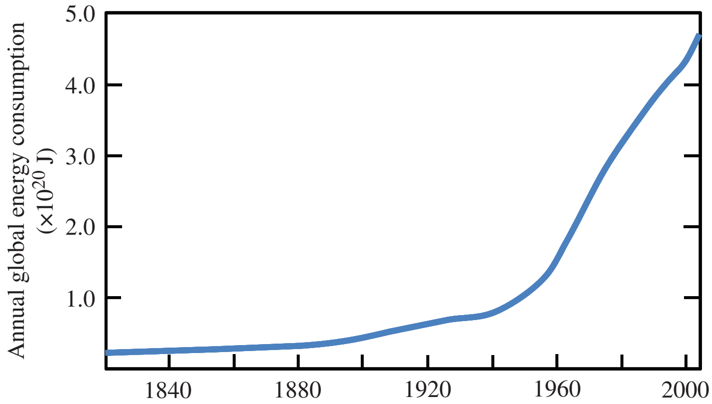

Figure 1.1 Illustration of the dramatic rise in annual global energy consumption that occurred between 1820 and 2010.

for comparison, contains ~1.5 MJ of energy. We also need energy to heat and light our houses, to run washing machines and refrigerators, to travel to work, to use computers, to fly to a foreign country on holiday, and so on. Furthermore, energy is needed to produce the food we eat, to manufacture and transport the goods we buy, etc. Overall, the total energy consumption per person per day in the UK is ~450 MJ. When we consider energy consumption, it is perhaps more meaningful to use the kilowatt-hour (kWh) unit of energy. This is the energy consumed by a 1 kW electric fire in 1 hour and the conversion factor is 1 kWh = 3.6 MJ. So 450 MJ/day = 125 kWh/day, which is the amount of power consumed by five 1 kW electric fires running day and night. This figure of 125 kWh per person per day is typical for a European country. In the USA, the energy consumption per person is about twice as high, while in underdeveloped countries it is considerably lower. Averaged over all countries, energy consumption is ~60 kWh per person per day and this amounts to a total global energy consumption of $\sim 5 \times 10^{20}$ J/year.

Global consumption of energy continues to increase because of advances in technology, growth in world population and economic growth, factors that are interrelated. Figure 1.1 illustrates the dramatic increase in annual global consumption of energy that occurred between 1820 and 2010. As an example of a technological advance, James Watt patented his steam engine in 1769 and this enabled the Earth's deposits of fossil fuels such as coal to be unlocked. This signalled a sharp increase in energy consumption, and once industrialisation occurred, the rate of consumption increased dramatically; over the course of the 20th century, global use of energy increased more than 10-fold. The world's population has also increased dramatically over the last few hundred years, rising from 1 billion in 1800 to 7.4 billion in 2016. Indeed the curves for global energy consumption and global population follow each other quite closely. Presently, global population is increasing at a rate of just over 1% per year. The rate of economic growth is different for different countries. However, averaged over all countries, economic growth also increases at about 1% per year. Taking the various factors into account, it is predicted that the growth in global energy consumption over the next 30 years will be ∼2% per year.

A complementary aspect of energy consumption is the efficiency with which energy is used. No source of energy is cheap or occurs without some form of environmental disruption, and it is important that energy is used as efficiently as possible. One particular advance can be seen in the use of electric light bulbs. It is estimated that lighting consumes about 20% of the world's electricity. Traditional incandescent light bulbs with a wire filament are only about 5% efficient, while new types of lighting are much more efficient. LED lighting, for example is about 20% efficient.

1.2 Energy sources

The main sources of energy available to us are:

- fossil fuels
- solar energy
- biofuels
- wind energy
- nuclear energy
- waves and tidal energy
- hydroelectric energy
- geothermal energy.

Most of the energy available to us comes directly or indirectly from the Sun. The Sun gets its energy from nuclear fusion reactions that heat its core to a temperature of $\sim 10^7$ K. Energy is transported to the Sun's surface and maintains the surface at a temperature of ∼6000 K. The hot surface acts as a blackbody radiator emitting electromagnetic radiation and it is this radiation or sunlight that delivers solar energy to the Earth. The total solar power that falls on the Earth is enormous, $\sim 1.7 \times 10^{17}$ W, which is about 25 MW for every person in the world.

Sunlight provides us with energy in various ways. *Photosynthesis* is the process by which plants and other organisms use sunlight to transform water, carbon dioxide, and minerals into oxygen and organic compounds. Fossil fuels that we burn, including oil, coal and natural gas, were formed over millions of years by the action of heat and pressure on the fossils of dead plants. *Bioenergy* comes from biofuels that are produced directly or indirectly from organic matter, including plant material and animal waste; an example is rapeseed oil, which produces oil for fuel. Wood also fits into this category and, indeed, burning wood is by far the oldest source of energy used by humankind. Hydroelectric power, wind power and wave power can also be traced back to the Sun. Solar energy heats water on the Earth's surface, causing it to evaporate. The water vapour condenses into clouds and falls as precipitation. This fills the reservoirs of hydroelectric plants, and the potential energy of the stored water provides a supply of energy. The Sun's warming of the Earth's surface produces winds that circulate the globe and which can be used to drive wind turbines. The winds also produce ocean waves whose kinetic energy can be harvested. More directly, solar energy can be captured by solar water heaters or alternatively by photovoltaic devices, which convert sunlight into electrical energy directly. The Sun even plays a role in the formation of the tides, which result from the motions of the Moon, Sun and Earth. The rising and falling tides contain potential and kinetic energies that can be harvested.

We also get energy from human-induced nuclear reactions. So far, nuclear power has exploited fission reactions of heavy, radioactive elements such as uranium. However, as we will see, nuclear fusion of light elements such as deuterium and tritium has great potential as an energy source of the future. Finally, the Earth itself is a source of energy called geothermal energy. This is stored as thermal energy beneath the Earth's surface. It results from the processes involved in the formation of the Earth and from the decay of radioactive elements within its crust and appears, for example, as hot water springs in various regions of the world.

The annual consumption of energy with respect to energy source varies from country to country and from year to year. However, to get an impression of energy consumption by energy source, Figure 1.2 shows the data for the USA in 2014. We see that 81% of energy consumption came from fossil fuels, while nuclear energy and renewable sources provided the remainder.

The energy sources listed above are called *primary* energy sources. Electricity, on the other hand, is described as a *secondary* energy source, as it derives from the conversion of energy from a primary source. Electricity has significant advantages as an energy carrier. It can be conveniently transported and distributed via a national grid, and for many energy needs it is easier to use than the primary energy source itself. The other important secondary energy source is hydrogen gas, which can be burnt or used in *fuel cells*.

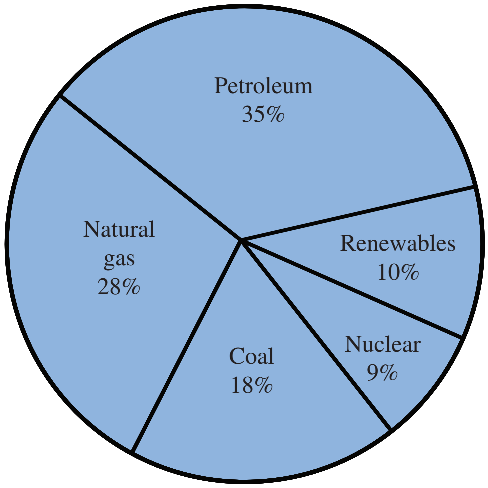

Figure 1.2 Annual energy consumption for the USA in 2014, by energy source – 81% of energy consumption came from fossil fuels, while nuclear energy and renewable sources provided the remainder.

1.3 Renewable and non-renewable energy sources

Energy sources can be classified as either renewable or non-renewable. We define a renewable source as one in which the energy comes from a natural and persistent flow of energy that occurs in the environment. Hydroelectric energy, solar energy, wind energy, wave energy, tidal energy and geothermal energy are renewable sources and so is bioenergy, so long as the trees and crops are replaced. Non-renewable sources are finite stores of energy, such as coal and oil, and nuclear fuels such as uranium. These non-renewable sources are not sustainable in the longer term. The distinction between renewable and non-renewable energy sources is illustrated in Figure 1.3. Closely associated with renewable energy sources is *sustainability*.

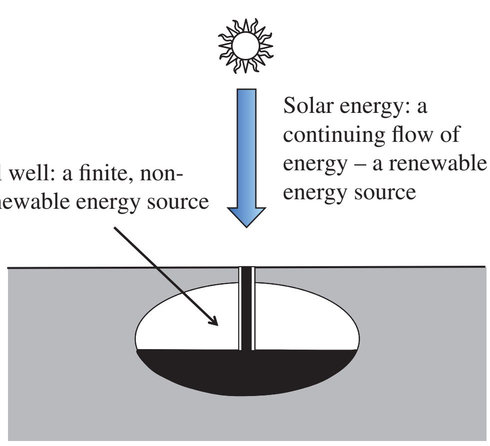

Figure 1.3 Illustration of the distinction between renewable and non-renewable energy sources, using the examples of solar energy and energy from the fossil fuel oil. Solar energy flows continuously from the Sun, while reserves of oil are finite.

Sustainable development can be broadly defined as living, producing and consuming in a manner that meets the needs of the present without compromising the ability of future generations to meet their needs. Renewable sources are much more compatible with sustainable development than non-renewable sources.

Fossil fuels, although non-renewable, have the advantage that their energy densities are high, i.e. they yield a large amount of energy per unit mass or per unit volume. For example, a litre of oil contains 35 MJ of energy. Moreover, the output of a power plant using fossil fuels is controllable. However, the burning of fossil fuels produces substantial amounts of pollution and increases the concentration of CO_2 in the atmosphere, which enhances the greenhouse effect. Nuclear fuels have an even higher energy density. In fact, their energy density is $\sim 10^6$ times greater than that of a fossil fuel and, again, the output of a nuclear reactor can be controlled. But, of course, nuclear power presents its own challenges, including the long-term storage of spent nuclear fuel. In general, renewable energy sources produce less atmospheric pollution than fossil fuels and do not emit CO_2 gas directly, the exception being the burning of biofuels. Furthermore, because they extract their energy from natural flows of energy that are already compatible with the environment, they produce minimum *thermal* pollution. They may also offer the possibility of a country becoming self-sufficient in energy. A disadvantage of some renewable sources is that they produce energy intermittently; solar cells need the Sun and wind turbines need the wind. Hence, the energy they deliver cannot be controlled in the same way as, say, a nuclear power station. However, this disadvantage is mitigated by the use of energy storage. Renewable energy is also usually more expensive than that obtained from fossil fuels, and renewable energy plants may have a significant impact on the local environment. For example, a hydroelectric plant can greatly affect the local ecology and may also cause the displacement of local inhabitants. At present, renewable sources contribute a much smaller fraction of global energy than do fossil fuels, although this fraction is expected to increase significantly in the future; presently, for example, renewable energy accounts for roughly a fifth of global electricity production.

1.4 The form and conversion of energy

According to the kind of energy they deliver, we can broadly divide sources into the following categories: thermal energy sources, mechanical energy sources and photovoltaic sources.

1.4.1 Thermal energy sources

Fossil fuels are a store of chemical energy that is a form of potential energy associated with the chemical bonds of the molecules of the fuel. Burning the fuel breaks these bonds and releases energy, mostly in the form of thermal energy. Nuclear fission reactions release potential energy that is stored in the nuclei that undergo fission and this energy becomes converted into thermal energy in the core of the reactor. In both cases, the thermal energy is converted into mechanical energy by a steam turbine, which is a type of *heat engine*. A fundamental aspect of the conversion of thermal energy into mechanical energy is that it is governed by the laws of thermodynamics, and these limit the efficiency of the conversion process, as we shall see in Chapter 4. For example, the efficiency of a conventional, coal-fired power plant for converting thermal energy into mechanical energy may be $\sim$35%. Alternatively, thermal energy can be used to heat buildings directly, thus avoiding thermodynamic limitations. Here, the thermal energy is transported as steam through large-diameter insulated pipes, and such *district heating* is common in some countries.

1.4.2 Mechanical energy sources

These sources deliver mechanical energy directly, as in the case of a wind turbine. The wind causes the blades of a turbine to rotate and the rotation of the turbine shaft delivers mechanical energy directly. Hence, the thermodynamic limitations of thermal to mechanical energy conversion are avoided. Nevertheless, methods of extracting mechanical energy from a particular source also have inherent limitations to their efficiency. In the case of a wind turbine, we will see that the maximum efficiency of a turbine for extracting energy from the wind is 59%.

1.4.3 Photovoltaic sources

Photovoltaic solar cells have the advantage that they convert sunlight into electrical energy directly so again the thermodynamic limitations of thermal to mechanical energy conversion are avoided. However, as we shall see, there are a number of factors that limit the efficiency of solar cells. In practice, the efficiency of a commercial solar cell for converting solar energy into electrical energy is $\sim$20%.

The efficiency with which a particular source of energy can be transformed from one form to another is described as the *quality* of the source. Waste hot water from a manufacturing process at 60°C would be described as low quality. This is because at this relatively low temperature the efficiency of a heat engine to convert the thermal energy of the water into mechanical energy is very low, less than 12%. On the other hand, electricity has high quality. For example, it can be converted into mechanical energy by an electric motor with very high efficiency, ∼95%.

1.4.4 Energy storage

Energy has to be provided when it is needed. Some energy sources, such as nuclear power stations and hydroelectric plants can provide a continuous supply of energy. On the other hand, sources such as wind turbines and solar cells produce energy intermittently; these sources may not generate enough energy when it is needed or, alternatively, they may generate excess energy. Energy storage systems allow the excess energy to be stored and used at a later time. And with increasing use of intermittent renewable sources, energy storage is becoming increasingly important. It is also the case that demand for energy varies substantially throughout the seasons and throughout the day; it tends to peak in the morning and afternoon, and fall to a minimum during the night. Power stations should ideally be operated at a fairly constant output level and close to where they operate most efficiently. But it does not make economic sense, and is a waste of energy, to have a power supply system whose capacity exceeds peak demand. Stored energy can supply the extra energy when required. So energy storage is able to even out variations in both supply and demand.

The chapters that follow deal with nuclear power, solar power, wind power and water power. Chapter 2 deals with the properties of the atomic nucleus, nuclear forces and radioactivity, and forms a foundation for the understanding of nuclear fission and nuclear fusion. These are dealt with in Chapter 3, which describes how we get energy from the nucleus, by both the fission of heavy nuclei and the fusion of light nuclei. Chapter 4 describes the origin and characteristics of solar radiation, its interaction with the Earth and how thermal energy can be harvested from sunlight. We also discuss the conversion of thermal energy into mechanical energy. Chapter 5 is devoted to semiconductor solar cells and their underlying principles of operation including the action of the *p–n junction*. Chapter 6 deals with the harnessing of wind power by wind turbines. Chapter 7 describes water power and the various ways in which the energy is harvested, including hydroelectric, wave and tidal power. Finally, Chapter 8 describes various ways in which energy can be stored for future use. Fossil fuels are not dealt with explicitly. However, fossil fuels are used to produce thermal energy that, in turn, produces steam to drive a turbine. In this respect they have much in common with, for example, nuclear power, where again the energy is first converted into thermal energy to drive steam turbines, and similar thermodynamic principles apply.

Problems 1

1.1 Show that 1 kWh = 3.6 MJ.

1.2 Estimate the amount of energy (in kWh) that is used for lighting in an average house in a year.

1.3 (a) Estimate the amount of energy in kWh/passenger for a round trip between London and New York, which are separated by a flying distance of 5600 km. Assume that the plane uses 12 L/km and that the plane has 400 passengers on board and that the fuel has an energy density of 36 MJ/L. (b) Compare this value with the amount of energy required to commute by car 5 days a week for 48 weeks. Take the distance travelled each day to be 30 km, the fuel consumption to be 15 km/L, the energy density of the fuel to also be 36 MJ/L and assume that there are no passengers in the car.

1.4 A particular chocolate bar contains 230 food calories. Through what vertical distance could this amount of energy, in principle, lift a 1 tonne motor car? Note that 1 food calorie = 1 kcal = 4.2 kJ.

2

The atomic nucleus

Radioactivity was discovered by Antoine Henri Becquerel in 1896. He found that the mineral crystal he was investigating caused a photographic plate to become blackened. It was an accidental discovery because he had been looking for the emission of X-rays from the crystal; X-rays had also recently been discovered. However, the crystal happened to contain some uranium, which produced the nuclear radiation. There followed a period of intense research on the nature of this radiation and the materials that emitted it. Marie and Pierre Curie isolated and identified the radioactive element radon, while Ernest Rutherford found three distinct forms of nuclear radiation, which he characterised by their ability to penetrate matter and ionise air. The first type of radiation, which penetrated the least, but caused the most ionisation, he called alpha (α) rays. The second type, with intermediate penetration and ionisation, he called beta (β) rays, and the third type, which produced the least ionisation but penetrated the most, he called gamma (γ) rays. It was subsequently discovered that α-rays are composed of helium nuclei, β-rays are composed of electrons and γ-rays are composed of high-energy photons. Becquerel, the Curies and Rutherford all received Nobel prizes for their discoveries. A turning point in the understanding of the atomic nucleus came in a series of pioneering experiments by Rutherford and his collaborators at the University of Manchester. They directed a beam of α particles at a thin gold foil and observed how the α particles were deflected by the foil. Based upon their observations, Rutherford postulated a model of the atomic nucleus that remains familiar today: a model in which all the positive charge of the atom and all the mass is concentrated in an extremely small region called the nucleus. It could be said that nuclear physics began with Rutherford's discovery of the atomic nucleus.

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In parallel with these experiments on the atomic nucleus there were the revolutionary developments of quantum mechanics and relativity. These considerably aided the understanding of the results of the experiments, and indeed these experiments provided convincing evidence for the validity of the new theories. In 1905 Einstein published his equation describing the equivalence of mass and energy:

$$E = mc^2. \tag{2.1}$$

Einstein's equation shows that huge amounts of energy are released when mass–energy conversion takes place, as happens in nuclear fission and nuclear fusion. The fission of heavy nuclei, such as uranium, is a major source of power today, while the fusion of light nuclei is the energy source that powers the stars, including our Sun, and has the potential to play a key role in providing the energy needs of the future. Nuclear fission and nuclear fusion are discussed in Chapter 3.

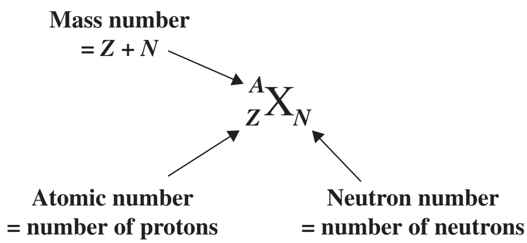
In this chapter we describe the composition of nuclei and their basic properties, including their size, mass and electric charge. The characteristics of the forces that bind the constituents of a nucleus together are also described together with the resulting nuclear *binding energies*. We will see how the binding energy is intimately related to the energy that we can obtain from nuclear fission and fusion through the equivalence of mass and energy. We will also see that binding energy plays a central role in the stability of nuclei and that unstable nuclei decay to more stable nuclei. The various ways in which radioactive decay can occur will also be described.

2.1 The composition and properties of nuclei

2.1.1 The composition of nuclei

At the centre of an atom is a positively charged nucleus. The nucleus is very small compared with the overall size of the atom; an atomic diameter is $\sim 10^{-10}$ m, while the diameter of a nucleus is $\sim 10^{-14}$ m, a factor of $\sim 10^4$ smaller. The nucleus contains just two kinds of particles, protons and neutrons. Protons and neutrons are much heavier than electrons, by a factor of approximately 2000, and so nearly all the atomic mass is concentrated in the nucleus. A nucleus is characterised by the number of protons and neutrons it contains. The number of protons is called its *atomic number* Z. Since a proton has a charge $+e$, where e is the magnitude of the electronic charge, the nuclear charge is equal to $+Ze$. The number of atomic electrons must be equal to the number of protons in the nucleus to maintain charge neutrality, and so an electrically neutral atom must therefore have

Z electrons. The number of neutrons a nucleus contains is called its *neutron number*, N. A neutron has a mass that is very close to that of a proton, but it is electrically neutral. The proton and neutron are collectively known as *nucleons*, as they are both found in the nucleus. The total number of protons and neutrons is called the *nucleon number*, A, which is more usually called the *mass number* or *atomic mass number* of the nucleus. (This follows, as nuclear masses are measured on a scale in which the proton and the neutron have masses that are close to one fundamental unit of mass. A is then the *integer* nearest to the ratio between the nuclear mass and the fundamental mass unit.) A particular species of nucleus is called a *nuclide* and is specified by its values of A, Z and N as:



where X is the chemical symbol. An example is ${}^{58}_{28}\mathrm{Ni}_{30}$, pronounced nickel-58. Note that we do not need to write both the chemical symbol and the atomic number because the chemical symbol tells us the value of Z; for example, every nickel atom has $Z = 28$. It is also usually not necessary to include N, as $N = A - Z$. Thus we can simply and conveniently write ${}^{A}\mathrm{X}$; for example ${}^{58}\mathrm{Ni}$. (Including Z and N is useful when we are trying to balance Z and N in a nuclear reaction or decay process.)

Naturally occurring samples of most elements contain atoms with the same atomic number Z but with different values of mass number A. Nuclides with the same Z but different N are called *isotopes*. Typically an element may have two or three stable isotopes, although some, like gold, have just one while iodine has nine. A familiar example is chlorine ($Z = 17$). About 76% of naturally occurring chlorine nuclei have $N = 18$, while 24% have $N = 20$. These fractions are called the *natural abundances* of the respective isotopes. The chemical properties of an element are determined by its atomic electrons. As different isotopes of the same element have the same number of electrons, they have the same chemical properties. On the other hand, different isotopes have slightly different physical properties – in particular, properties that depend on mass. For example, the ${}^{235}_{92}\mathrm{U}$ and ${}^{238}_{92}\mathrm{U}$ isotopes of uranium can be physically separated because of the slightly different diffusion coefficients of the gases ${}^{235}_{92}\mathrm{UF}_6$ and ${}^{238}_{92}\mathrm{UF}_6$. This has important application in enriching naturally occurring uranium for nuclear fission reactors.

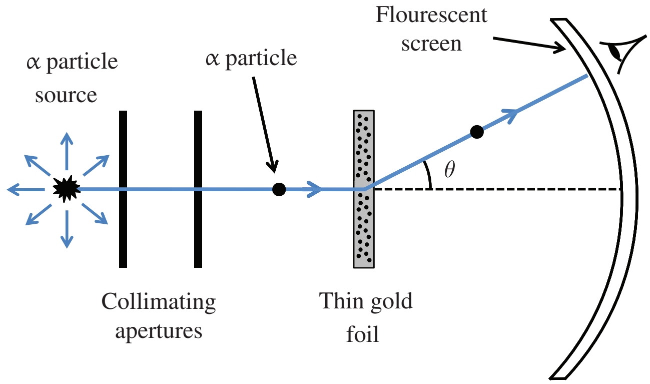


Figure 2.1 Schematic diagram of Rutherford's apparatus for observing the scattering of α particles by a thin gold foil. α particles from the source are collimated into a narrow beam and directed at the foil. The angle θ through which an α particle is deflected at the foil is measured by observing the point at which the particle strikes the fluorescent screen.

2.1.2 The size of a nucleus

A measure of nucleus size was first obtained by Rutherford and his collaborators, Hans Geiger (inventor of the Geiger counter) and Ernest Marsden, the latter still being an undergraduate student at the time. Rutherford had already established that α particles are doubly ionised helium atoms, He^{++}, where both electrons have been removed from the atom. He then used α particles as a *probe* of the nucleus. In these experiments, beams of α particles were fired at thin metal foils and the way these particles were deflected or *scattered* by the foils was investigated. (Firing energetic projectiles at sub-atomic particles remains, of course, a principal means of investigating their nature.) These investigations culminated in Rutherford's model of the structure of the atom: *all the positive charge of the atom, and consequently all the mass, is concentrated in an extremely small region called the nucleus.*

The Rutherford scattering experiment

A schematic diagram of the apparatus for Rutherford's scattering experiment is shown in Figure 2.1. The radioactive source emits α particles of well-defined kinetic energy E. This energy is typically about 5 MeV[1] and is measured in a separate experiment by observing the motion of the α particles in crossed electric and magnetic fields. The α particles are collimated into a narrow beam using a combination of apertures and are directed onto a thin gold foil. The foil is so thin that most of the α particles pass through it with little energy loss. However, the charged α particles suffer deflections

[1] The electron volt (eV) is defined as the energy that an electron gains when it falls through a potential of 1 volt. It is equal to 1.602×10^{-19} J. The eV is a convenient energy unit for atomic energies, while MeV $= 10^6$ eV is a convenient unit for nuclear energies.