Chapter 4 Ionising Radiation

The spectrum of radiation

So what exactly is radiation? The simplest answer is that it is energy on the move – and there are many kinds. Sunshine, music and waves on the surface of water are examples. At low levels many are quite harmless and even beneficial to life. Extreme levels can cause damage in almost every case – very loud music can damage hearing, and too much sun causes sunburn. However, a little sunshine is positively good for the skin by promoting the production of important vitamins. Similarly music that is not too loud may be positive and uplifting.

There is an important point here. It is not that gentle music causes only a little damage, but that it causes no damage to hearing whatever. When compared with the damage due to excessively loud sounds, the effect is not proportionate. Technically such a relationship is termed non-linear and this will be an important idea in subsequent chapters. In the case of music and damage to hearing the non-linearity may be obvious, but for other forms of radiation the distinction between proportionate and non-proportionate response will need to be looked at using both experimental data and an understanding of what is happening.

Most of the radiation from the Sun comes in the form of electromagnetic waves – this includes light and other parts of a wide spectrum. Each such wave involves entwined electric and magnetic fields. It has a frequency and an intensity just as a sound wave has a pitch and a volume. Our understanding of electromagnetic waves dates from the work of James Clerk-Maxwell in the 19th century, who built on the work of Michael Faraday and others. As for any wave, the speed at which it moves is equal to the frequency times the wavelength. Since the speed is essentially constant, the wave may be labelled by its
wavelength instead of its frequency, but either will do. On a radio receiver, for example, some stations are labelled by their frequency in MHz (mega-hertz, millions of waves per second), while for others the wavelength in metres is used. The product of the two is the speed of radio-waves, 300 million metres per second, the same as that of light.

How a wave is received is determined largely by the frequency not the intensity. For example, a radio receiver selects a station
by choosing its frequency rather than its loudness. In the same way that for sound there are frequencies that cannot be heard by the ear, so for light there are frequencies that are invisible to the eye. In fact only a tiny range of frequencies of electromagnetic waves is visible. The whole spectrum is represented in Figure 3 with a logarithmic frequency scale running up the page and covering more than 15 powers of 10, as shown in the second column in oscillations per second (Hz). The first column gives the corresponding wavelength. Visible light with its characteristic spectrum of rainbow colours is the narrow cross-hatched band half way up the diagram. The point is that there really is no fundamental difference between these waves, from radio through light to X-rays, except the frequency. At the highest frequencies (and shortest wavelengths) the powers of 10 become harder to cope with and a third scale based on the electron volt (eV) is often used.\footnote{11} This is shown on the right of Figure 3 with the usual prefixes for powers of 10.\footnote{12}

Much benefit has been brought to everyday life through enabling mankind effectively to see using these other frequencies [4]. Lower in the diagram are radio-waves up to $10^9$ Hz, used for example in MRI to see inside the human body and in radar to see ships and planes in fog and darkness. Slightly higher is thermal imaging, used to see warm bodies accidentally buried or concealed. Just below the visible frequencies is a region called the \textit{infrared absorption band}, shown as shaded in the diagram. At these frequencies many materials are opaque because the rotation and vibration of molecules are in tune and resonate with electromagnetic waves. Above the visible there is another band, the \textit{ultraviolet absorption band}. Here it is the more nimble atomic electrons that are in tune and the cause of the absorption. So here too materials are opaque, as marked by the shading.

\footnote{11}{The electron volt is $1.6\times10^{-19}$ joules. This is a useful scale in the atom. The electron in the hydrogen atom has an energy of 13.6 eV while typical nuclear energies are in MeV.}

\footnote{12}{\(\mu\) or micro, one millionth.  \(m\) or milli, one thousandth.  
\(k\) or kilo, one thousand.  \(M\) or mega, one million.  \(G\) or giga, one billion.}
Heavier elements with their more tightly bound electrons have an ultraviolet absorption band that extends to much higher frequencies than light elements. This is the frequency range of the X-rays. Here, metals like copper and calcium absorb radiation whereas carbon, hydrogen and oxygen are transparent. Medical images of a patient's teeth or bones (calcium) illuminated with such radiation show clearly any fracture or disease because the enveloping tissue (carbon, hydrogen and oxygen) is transparent.

Above about 100 keV atomic electrons, even those that are most tightly bound in the heavier elements, cannot move fast enough to follow the oscillating wave. Consequently there is no resonance and all materials are largely transparent. This region is called the gamma ray region. Historically the distinction between X-rays and gamma rays depended on the source – electrons and nuclei, respectively. This distinction is deceptive because their effect does not depend on the source, only on their energy (or frequency). Today this switch of name is usually made at about 100 keV, but the distinction is really only a convention. Gamma rays are very penetrating, being only weakly absorbed, which is why they are used in radiotherapy to target energy into a cancer tumour, deep within a patient's body. This energy may then be absorbed in the tumour with sufficient intensity that its cells are killed and it ceases to function. There are practical difficulties in doing this, as discussed later in Chapter 7.

**Damage from radiation**

So understanding light, and then learning to see with radiation in other parts of the spectrum, is really useful. But what of the risks? The spectrum can be divided roughly into two halves separated at about 10 eV. Radiation of greater frequency or

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13 At such high frequencies the radiation appears less like waves and more like rays, or particles. In quantum mechanics this distinction has no real substance, and electromagnetic waves of any frequency \( f \) come in bundles of energy called *photons*, \( E = hf \), where \( h \) is Planck's Constant. Each atom or nucleus emits one such bundle or particle when it decays.
energy is called *ionising radiation*, that below, *non-ionising radiation*. The distinction is that ionising radiation can ionise and break molecules apart – this is the radiation with which this book is primarily concerned.

Public concern about weak levels of non-ionising radiation, for instance from overhead power lines or mobile phones, is misplaced. The only known way in which such radiation can cause damage is by heating.\(^{14}\) Put briefly, these radiation sources are safe if heat is not sensed – even then, benefits may dominate over any reasonable risk. Warmth from sunshine or a domestic fire is brought by the same kind of radiation as that in a microwave oven. While the radiation levels in such an oven can certainly be dangerous, the heat radiated by a glowing fire on a cold winter's day is a quite acceptable source of radiation hazard for most people – in spite of the fact that its heat level can be sensed, indeed because of it.

But non-ionising radiation still has a crucial environmental impact. On the right hand side of Figure 3 are two boxes labelled *sunshine* and *earthshine*. Very hot materials like the Sun emit light in the visible region, but cooler materials also emit, though predominantly in the infrared frequency range. The sunshine box indicates the range of frequencies that the Sun emits. Because this is centred on the visible region for which the atmosphere is largely transparent, much of this radiation reaches the surface of the Earth for the benefit of all, including plant life. (Actually the spectrum of the Sun extends a bit into the infrared and ultraviolet, too – the infrared part provides warmth, the ultraviolet causes sunburn, if not filtered by barrier cream and the small concentration of ozone present in the upper atmosphere.) The earthshine box indicates the frequency band of radiation that the surface of the Earth emits with its lower temperature – but not all of this radiation succeeds in getting out

\(^{14}\) This important statement can be scrutinised but the effect of radio-waves and microwaves on living tissue is well understood and they are widely used. For instance, they are used in MRI, safely below the level at which any significant heating occurs.
of the atmosphere because of infrared absorption by polyatomic gases,\textsuperscript{15} in particular carbon dioxide, water vapour and methane. With an atmosphere containing more of these the Earth is not able to cool itself nearly as effectively as it is able to absorb the sunshine. So energy is trapped in the atmosphere and the temperature increases. Crudely, this is how the \textit{Greenhouse Effect} works. If the concentration of these gases rises, the Earth gets hotter and the climate changes. An extraordinary example is close at hand – Venus has a surface temperature of 460ºC, thanks in part to an atmosphere with 97% carbon dioxide.

Like electromagnetic waves, beams of charged particles such as alpha and beta radiation can also damage molecules, so that they are classified as ionising radiation – and beams of neutrons and other ions too, although these are less common in the natural environment.

\section*{Nuclear stability}

But what makes a nucleus decay? Or rather, what holds it together in the first place? The mutual electrical repulsion of the protons makes large nuclei more unstable than small ones. Stability only comes from the nuclear force that attracts neighbouring protons and neutrons together. This nuclear force overwhelms the electrical repulsion, but only at short distances within about $10^{-15}$ metres. As a result it favours small nuclei for which the protons and neutrons can huddle close together. The result is a balance between the preferences for nuclei to be not too large and not too small, which gives rise to the nuclear stability curve, Figure 4. The most stable atoms are those with nuclei at the highest point on the curve, the tightest average binding. These are in the region of iron, $A = 56$.

While quantum mechanics prefers nuclei with roughly equal numbers of protons and neutrons, the disruptive electrical force

\textsuperscript{15} Molecules like oxygen and nitrogen with just two atoms each do not vibrate and rotate with the same readiness that most polyatomic molecules do with all their many modes of internal movement. So they do not absorb much.
makes nuclei with too many protons unstable. The result is that all stable nuclei, except the largest, have roughly equal numbers of protons and neutrons, so that iron ($Z = 26$) has 30 neutrons. As shown in Figure 4, for smaller values of $A$ the binding effect of the nuclear force is reduced; at larger values of $A$ the disruptive influence of the electrical effect is increased – either way the binding is less. Above iron the compromise favours nuclei with more neutrons than protons because the disruption only acts on the protons. So for example, the most abundant isotope of lead, lead-208, has 82 protons but 126 neutrons. There are no naturally occurring elements above uranium ($Z = 92$) – those above actinium ($Z = 89$) are collectively referred to as the actinides.

The curve shows that in principle nuclei with small $A$ could fuse together to release energy due to the nuclear force, as shown by the arrow on the left. This is nuclear fusion and the source of stellar energy, including that of the Sun. In addition, nuclei with large $A$ can in principle release energy by splitting apart and moving towards greater stability as shown by the arrow on the

**Figure 4** The average binding energy per proton or neutron as it depends on the atomic mass number, $A$. 

![Graph showing the average binding energy per proton or neutron as a function of atomic mass number.]
right. This is nuclear fission.\textsuperscript{16} Because, like lead, the parent nucleus has more extra neutrons than its stable fission products, there are excess free neutrons emitted in the fission process. The liberation of these extra neutrons is crucial to the nuclear chain reaction mechanism.

In practice fission is very rare. Alpha decay in which a heavy nucleus splits into helium and a smaller nucleus is more common. This is the source of much of the natural radioactive energy in the Earth's crust – the energy source of natural geothermal power, in fact. In alpha decay nuclear energy is released by moving to the left along the curve in steps of four units in \( A \). As \( A \) reduces, the excess proportion of neutrons has also to be reduced, and this occurs by beta decay in which a neutron in the nucleus decays emitting an electron and leaving behind an extra proton within the nucleus.

Table 2 The four distinct primordial radioactive series with their head members and half-lives (\( T_{1/2} \)), and also end members. \( T_{1/2} \) is given in G-year, a thousand million years.

<table>
<thead>
<tr>
<th></th>
<th>4( n ) series</th>
<th>4( n +1 ) series</th>
<th>4( n +2 ) series</th>
<th>4( n +3 ) series</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>thorium-232</td>
<td>neptunium-237</td>
<td>uranium-238</td>
<td>uranium-235</td>
</tr>
<tr>
<td>( T_{1/2} )</td>
<td>14.1 G-year</td>
<td>0.002 G-year</td>
<td>4.5 G-year</td>
<td>0.70 G-year</td>
</tr>
<tr>
<td>End</td>
<td>lead-208</td>
<td>bismuth-209</td>
<td>lead-206</td>
<td>lead-207</td>
</tr>
</tbody>
</table>

The natural radioactivity of heavy nuclei consists of a sequence of alpha and beta decays in which energy is released as the nucleus moves to lower \( A \) along the stability curve (Figure 4). There are four distinct series of nuclei, depending on whether \( A \) is of the form \( 4n \), \( 4n+1 \), \( 4n+2 \), or \( 4n+3 \), where \( n \) is a whole number. Within each series nuclei may decay, one into another, by alpha or beta decay. Each series has a long-lived primordial head member and an end member which is effectively stable –

\textsuperscript{16} It is curious to note that in nuclear fission it is stored \textit{electrical} energy that is released. Energy due to strong nuclear binding is absorbed, not released, in the fission process.
these are given in Table 2. The $4n+1$ neptunium series has already died out, but the other three are still active in the natural environment. The successive members of the $4n+2$ series, with their decays and half-lives, are shown in Table 3, as an example.

<table>
<thead>
<tr>
<th>Element-(A)</th>
<th>(Z)</th>
<th>(N)</th>
<th>Decay</th>
<th>Half-life</th>
</tr>
</thead>
<tbody>
<tr>
<td>uranium-238</td>
<td>92</td>
<td>146</td>
<td>alpha</td>
<td>4.5 G-year</td>
</tr>
<tr>
<td>thorium-234</td>
<td>90</td>
<td>144</td>
<td>beta</td>
<td>24.1 day</td>
</tr>
<tr>
<td>proactinium-234</td>
<td>91</td>
<td>143</td>
<td>beta</td>
<td>1.17 minute</td>
</tr>
<tr>
<td>uranium-234</td>
<td>92</td>
<td>142</td>
<td>alpha</td>
<td>240 k-year</td>
</tr>
<tr>
<td>thorium-230</td>
<td>90</td>
<td>140</td>
<td>alpha</td>
<td>77 k-year</td>
</tr>
<tr>
<td>radium-226</td>
<td>88</td>
<td>138</td>
<td>alpha</td>
<td>1.6 k-year</td>
</tr>
<tr>
<td>radon-222</td>
<td>86</td>
<td>136</td>
<td>alpha</td>
<td>3.82 day</td>
</tr>
<tr>
<td>polonium-218</td>
<td>84</td>
<td>134</td>
<td>alpha</td>
<td>3.05 minute</td>
</tr>
<tr>
<td>lead-214</td>
<td>82</td>
<td>132</td>
<td>beta</td>
<td>26.8 minute</td>
</tr>
<tr>
<td>bismuth-214</td>
<td>83</td>
<td>131</td>
<td>beta</td>
<td>19.8 minute</td>
</tr>
<tr>
<td>polonium-214</td>
<td>84</td>
<td>130</td>
<td>alpha</td>
<td>164 microsecond</td>
</tr>
<tr>
<td>lead-210</td>
<td>82</td>
<td>128</td>
<td>beta</td>
<td>22.3 year</td>
</tr>
<tr>
<td>bismuth-210</td>
<td>83</td>
<td>127</td>
<td>beta</td>
<td>5.01 day</td>
</tr>
<tr>
<td>polonium-210</td>
<td>84</td>
<td>126</td>
<td>alpha</td>
<td>138.4 day</td>
</tr>
<tr>
<td>lead-206</td>
<td>82</td>
<td>124</td>
<td></td>
<td>metastable</td>
</tr>
</tbody>
</table>

### Measuring radiation

To speak usefully of the effect on human life of different doses of ionising radiation, these must be measured, somehow. But how exactly?
The first step in quantifying a radiation exposure is to measure how much energy is absorbed per kilogram of living tissue during the exposure. This energy may cause chemical damage by breaking molecules apart that leads to biological (cellular) damage and finally to clinical damage, such as cancer or other disease. Such clinical damage turns out to be more difficult to relate to the exposure, especially as it may manifest itself in different ways, and on long or short timescales, from days to years.

In earlier decades knowledge of cell biology was too primitive to provide confident understanding, and adequate evidence of the effect of radiation on humans was not available to corroborate any particular view. In their absence, and for lack of anything better, the knowledge gap was bridged by a rule of thumb – a model in science-speak. This is the Linear No-Threshold model, abbreviated LNT. This assumes that clinical damage is in simple proportion to the initial radiation energy dose. No justification was given for it, but it was a reasonable working hypothesis at the time. Despite the poor state of knowledge, a start had to be made somewhere.

However, given modern biological knowledge and extensive records of human data, this model is now redundant and many of its more cautious implications can be ignored. The details are for discussion in later chapters. First, we return to the questions of the quantification of radioactivity and absorption of radiation energy in materials.

The rate at which energy is emitted by a radioactive source depends on the number of radioactive nuclei $N$, the energy of the decay, and the half-life $T$ of the nucleus. The value of $N$ is reduced by half with every successive time interval $T$ and the average activity is proportional to $N/T$. Activity is measured in decays per second, called becquerel and abbreviated Bq. Sometimes the activity may be measured in a cubic metre of material, thus Bq m$^{-3}$.

So what does this mean in practice? Contamination by radioactive nuclei with a short half-life results in high activity for
a short time; the same contamination with a longer half-life results in a lower activity, but it continues for longer. Half-life values vary between a small fraction of a second and many times the age of the Earth. So sources of radioactive contamination with short half-lives fade away while others with longer half-lives continue on. This is in contrast to most chemical pollutants, such as heavy metals like mercury or arsenic, that remain hazardous indefinitely. A slightly different situation arises when a dose of ionising radiation energy comes from an external beam produced by an accelerator (such as an X-ray machine) or from an external radioactive source.

Either way the important question is, how far does the radiation travel in material before being absorbed? Some radiation is so strongly absorbed in air, or any thin material, that it never reaches human tissue unless the source is on the skin or inside the body. Other radiation is weakly absorbed and can pass through the body. So what is important is not the intensity of the radiation, but the amount that is absorbed, for instance, per kilogram of tissue.\(^{17}\) The extent to which it is absorbed depends on the kind of radiation and its energy (or frequency).

Alpha radiation is stopped even by air, and so the decay energy is deposited very close to the site of the radioactive contamination itself, with no dose at all only a little further away. An example is the energetic, but short range, alpha radiation emitted by the decay of the radioactive isotope polonium-210. A large internal dose of this was used allegedly by Russian agents to kill Alexander Litvinenko in London in 2006. No energy escaped the immediate location of the poison but there the tissue received the full radiation energy dose.

Beta decay produces electrons that travel further in material and, therefore, the deposited energy dose is more diffusely distributed around the radioactive source. Gamma rays go further still. So for a radioactive source in rock, for example, any alpha and most

\(^{17}\) Radiation that just passes through and does not deposit any energy is necessarily harmless – like the neutrino radiation mentioned on page 31.
beta radiation is absorbed internally within the rock, and only the gamma radiation escapes to give an external energy deposition. In general a deposited energy dose is quantified as the number of joules of energy absorbed per kilogram of material, such as patient tissue. One joule per kilogram is called a gray (Gy). Typically doses are measured in milligray, with a milligray (mGy) being one thousandth part of a gray.

The clinical damage caused to living tissue by this deposited radiation develops as a result of a number of steps.

1. The immediate molecular mayhem left by the radiation.
2. Biological damage in which living cells are put out of action – this changes with time as the tissue responds to the radiation dose.
3. The incidence of cancer (and other possible delayed or heritable effects) related to the exposure, perhaps decades later.
4. The reduction in life expectancy as a result of such cancers (this effect on life expectancy is called the radiation detriment of the exposure).
5. The chance of death shortly after exposure due to acute radiation sickness brought on by cell death and the shutdown of the normal biological cycle in one or more vital organs.

The two lasting consequences for life are described by the sequences 1-2-3-4 and 1-2-5, and later we will discuss how each of these outcomes relates to the initial radiation energy dose.

There are other causes of cancer, unrelated to radiation. Some causes – we shall refer to them generally as stresses – are natural, others are imposed by choice of lifestyle. Following decades of study much is known about how these stresses are related to the occurrence of cancer – to the detriment in fact. An important question is how the outcome is influenced when there is more than one stress. These stresses may be quite independent, as in smoking and radiation, but the result may not be. There remain some unanswered questions. But the point is that the range of residual uncertainty is too small to prevent mankind from taking
decisions now about how radiation can be used with effective safety.

For a single acute dose the damage is related to the size of the dose and the type of radiation. The effects of X-rays, $\gamma$-rays and electrons are found to be roughly the same for the same energy dose in milligray. However, for other types of ionising radiation the biological damage is different. Quantitatively, the measured ratio of damage relative to X-rays is called the relative biological effectiveness (RBE). So the RBE of a radiation dose indicates how much more clinical damage it causes than is caused by the same number of milligray of energetic gamma rays. Essentially these RBE factors are measured quantities.

RBE factors vary with the clinical end point – that is with the cancer or disease concerned. Timing effects are important and we look at these later. The variation with radiation type is particularly interesting although not too large. For most practical applications of radiation safety, which we are thinking about in this discussion, we need to watch the factors of ten, a hundred and a thousand. RBE factors close to one are less important. Only in radiotherapy are the effects of radiation very finely balanced – but in that case gamma rays are usually used and so RBE is 1.0 anyway. So for this simplified discussion it is sensible to ignore the RBE factor in the first instance.

Nevertheless the International Commission for Radiological Protection (ICRP) has felt it necessary to include RBE in some way. In their radiation safety standards they multiply each energy dose in gray by a weighting factor, $w_R$, which plays the role of a broad-brush averaged RBE. [They define $w_R$ for protons to be two; for alpha, fission fragments and other heavy ions to be 20; for neutrons it depends on the energy; for electrons and photons it is just one, by definition.] The result they define to be the equivalent dose, measured in units of sievert (Sv) – or millisievert (mSv). In ignoring RBE initially we treat doses measured in milligray and millisievert as equivalent, and come back later to the distinction when a variation in the type of
radiation has something special to say about how radiation damage occurs.

These measures of energy deposited (and equivalent dose) may be for a single acute exposure. It is observed that cell damage is different if the dose is spread over a period of time, either as a series of repeated exposures, or as a continuous chronic rate of exposure. The question is why? What is the radiation detriment resulting from a chronic rather than an acute radiation exposure? How does the effect of a single dose of so-and-so many milligray compare with the effect of a continuous dose rate of a number of milligray per day – or per year? The matter is not simple, because dose and dose rate are quite different measures. This is the subject of Chapter 7.

**Natural environment**

![Pie chart showing the origins of the average annual radiation exposure of the UK population, total 2.7 millisievert per year [5].]

The radiation dose rate experienced by the population of the UK varies from one place to another. The average is 2.7 millisievert per year, and a breakdown of this radiation by source is summarised in Figure 5.

The slice labelled *cosmic* is for radiation that originates from space. The *radon* and *gamma* slices describe natural radioactive
sources in nearby materials such as water, soil and rock. The *internal* radiation slice relates to the decay of radioactive atoms that occur naturally within the human body. The artificial part of the exposure is predominantly medical – the average due to all other man-made sources amounts to less than 0.5%.

The ionising radiation incident on the Earth from space is made up of electromagnetic radiation, protons and electrons. Some of the charged particle radiation comes from the Sun where the erupting magnetic fields of sunspots act as accelerators. At the top of the atmosphere this radiation causes ionisation, and the resulting discharges may be seen as the *Northern Lights* or aurora. Charged particles with low energy are deflected by the Earth's magnetic field, except in the magnetic polar regions, which is why the aurora are seen there. The resulting increased ionisation of the upper atmosphere affects satellite and radio communications, and when there is a magnetic storm this ionisation is high. None of these phenomena has any effect on health and the ionisation radiation does not reach the ground.

Cosmic radiation also includes protons that are more energetic and come from outside the solar system, and even outside the galaxy. These suffer nuclear collisions in the upper atmosphere. Some collisions create neutrons that then hit nitrogen nuclei high in the atmosphere to form the famous isotope, carbon-14. Although only 7.5 kg is created in total in the atmosphere each year, this is sufficient to maintain the proportion of carbon-14 in the natural biosphere (1 part in $10^{12}$), which provides the basis of radiocarbon dating. This isotope decays with a half-life of 5,700 years, and its concentration starts to fall as soon as material, animal or vegetable, dies – that is, stops refreshing its carbon from the air or digesting other living tissue. By measuring its concentration, materials can be dated. Famous examples are the Turin Shroud, the Ice Man from 3,300 BC found in the Otztal Alps in 1991, and bottles of fake 'old' whisky.

The most energetic protons from space create showers of subatomic particles, most of which decay or are absorbed by the atmosphere. The only radiation that reaches the ground is a flux
of muons$^{18}$ and this is responsible for the cosmic slice in Figure 5. At sea level this delivers about 0.6 millisievert per year in polar latitudes. In equatorial regions the flux is three times smaller because of the shielding effect of the Earth's magnetic field, which sweeps incoming protons away into space. The radiation rises rapidly with height above sea level because of the reduced absorption by the atmosphere.

In the very distant past the flux of radiation was much greater. The Universe itself started from a simultaneous explosion, known as the Big Bang, 13.8 billion years ago. The early stages were dominated by particle physics of the kind studied on a small scale at modern research accelerators. After a few minutes the explosion had cooled sufficiently for the distinct nuclei of hydrogen and helium to emerge. But, until 300,000 years later it remained so hot that electrons and nuclei were not bound together. As it cooled further, the heat radiation became non-ionising and atoms of hydrogen and helium appeared for the first time.

Over the next few billion years galaxies and stars formed. These evolved through nuclear fusion in massive stars, creating the heavier atoms that we see around us today, a process called nucleosynthesis. Slowly, as the Universe began to settle down, systems of planets formed in the neighbourhood of rotating stars, often composed of lumps of nuclear ash made spherical by gravity. Interplanetary fragments collided with the larger planets and their moons, leaving craters on the surfaces of those without an atmosphere.

This all happened before about 4.5 billion years ago when the Earth was formed and activity became quieter. Ionising radiation still reaches the Earth from hot stars in the form of heat radiation and from exceptional acceleration processes elsewhere in the Universe.

$^{18}$ The muon is an unstable subatomic particle with the properties of a heavy electron, which decays with a half-life of 1.4 microseconds.
Meanwhile nuclei of the four radioactive series (described in Table 2 on page 42) created during the period of nucleosynthesis continued to decay, although the neptunium series died out long ago. The other three are still going. The abundance of thorium in the Earth's crust is 3 to 10 parts per million by weight. For uranium-238 it is 1.8 to 2.7 parts per million. These values vary depending on the rock formation. There are significant quantities of uranium in sea water because its salts are soluble, unlike those of thorium. Within all natural uranium ores the ratio of uranium-235 to uranium-238 is currently 0.7%. This varies very little as the physical and chemical properties of the two isotopes are almost identical (see page 27) and their relative proportion does not naturally become diluted or enriched except through decay. Highly refined materials may be free of radioactivity but they are exceptional. Wood, concrete, glass and metals are all radioactive to some degree because they contain traces of natural radioisotopes.

A few primordial radioactive nuclei are not members of the four radioactive series. The most abundant is potassium-40 with a half-life of 1.27 billion years. It decays by beta decay, either to calcium-40 or to argon-40, both of which are stable. Potassium is a common element in the Earth's crust (2.1% by weight) and in sea water (0.044%). The regular stable isotope, potassium-39, is the most common and the unstable potassium-40 is only a tiny proportion (0.01117%). Potassium is essential to the electrochemistry of living cells and forms about 0.15 kg of human body weight. Other radioactive isotopes, such as carbon-14, with shorter lives are found in the environment too, being created afresh by cosmic radiation. Thus carbon-14 and potassium-40 between them account for 7,500 radioactive decays per second in an adult human body. The annual dose from such internal radiation is 0.25 millisievert (see Figure 5).

Two billion years ago the radiation from these nuclei was much as it is today, except that the proportion of uranium-235 in natural uranium was higher. In fact, from the measured half-lives (see Table 2) it is straightforward to calculate that at that time
natural uranium contained 3.5% of the faster decaying uranium-235. Today, some nuclear fission reactors use uranium fuel artificially enriched to this proportion, with ordinary water acting as coolant and moderator, in order to maintain a steady nuclear chain reaction. Two billion years ago such enriched fuel and water were available naturally, so that a similar nuclear reactor could occur by itself under the right circumstances. Clear evidence that this actually happened has been found in Gabon, West Africa. This natural nuclear fission reactor, known as the Oklo Reactor [6, 7], ran on its own for up to a million years. In our own time the extraordinary evidence came to light with the discovery that the relative abundance of uranium-235 in this particularly rich uranium deposit lay outside the narrow range found elsewhere in the world. It has been shown that the missing uranium-235 was consumed in the natural reactor cores and that the remains of the resulting fission products are still to be found there. This is significant because this reactor was not decommissioned and buried in a specially selected underground site at great cost. The residue of the uranium fuel and its fission products were left where they lay and have not moved in two billion years. This is an important demonstration of the stability that nuclear waste deposits can have over extremely long periods.

Radiation from radioactive sources in materials such as water, soil or rock reaches the external environment mainly in the form of gamma radiation and radon – alpha and beta radiation are mostly absorbed. Radon is a noble gas with little chemical activity, like helium, neon, argon, krypton and xenon. The isotope radon-222 has a half-life 3.82 days and is formed in the uranium-238 series (Table 3). This radioactive gas, once it has been released into the air, can be inhaled into the lungs where it may be absorbed and decay by alpha emission leaving polonium-218, a non-volatile isotope which decays with a sequence of further alpha emissions. Such alpha radiation has a short range and deposits all its energy in the lungs. On this basis radon would be expected to be a significant source of risk to the health of those who ingest it every day where they live and work.
Figure 5 shows radon as a large component of the average human radiation exposure. In fact, it is larger by factors of five or more in certain places, depending on the local geology. A significant question, discussed in Chapter 7, is whether this large variation is reflected in the local incidence of lung cancer.