# Chapter 2
# What Are Radioactivity and Radiation?

*All composed things tend to decay.*

Buddha 563–483 B.C.

We and everything around us are made of atoms. The idea of the atom came out of ancient Greek philosophy: some philosophers (notably Aristotle) thought that matter could be divided into ever smaller parts, and others (notably Democritus) thought that at some point, there was a minimum size of object, which they called "atomos", meaning "unsplittable". With the techniques of modern science, it has become clear that these atoms do exist, and each one is about a ten-billionth of a metre across: the full stop at the end of this sentence is about a million atoms across.

Ironically, we now know that atoms are not unsplittable: they are made up of smaller components. Each atom is composed of a small, positively charged nucleus, with some (negatively charged) electrons orbiting around it. The nucleus at the centre of the atom contains almost all of the atom's mass, but is a small fraction of the size, about a million-billionth of a metre across. This means that, in size terms, the nucleus inside an atom is in the same proportion as a grain of sand in a hot air balloon. A diagram of an example atom, with the size of the nucleus exaggerated, is shown in Figure 2.1.

Because very large and very small numbers occur frequently in this book, we will sometimes use the notation using powers of ten. This is a number written as a superscript by the number ten, and indicates how far the start of the number is from the decimal point.[1] Large numbers have a positive power of ten (so 1 000 000 is written $10^6$), and small numbers have negative power of ten (so 0.000 001 is written

[1] This can also be thought of as "how many times we should multiply (positive superscript number) or divide (negative superscript number) by ten". So $10^4$ is $10 \times 10 \times 10 \times 10$, which is 10 000; $10^{-3}$ is $\frac{1}{10} \times \frac{1}{10} \times \frac{1}{10}$, which is 0.001; and $4 \times 10^{-2}$ is $4 \div 10 \div 10$, which is 0.04.



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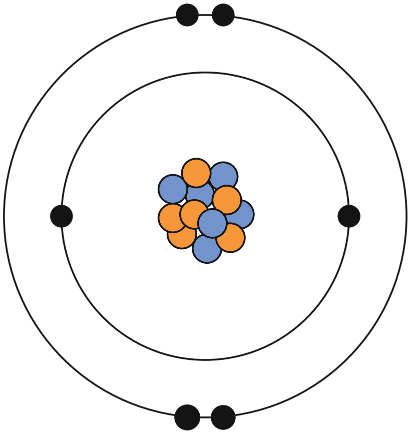


**Fig. 2.1** A diagram of an atom of carbon-12. The size of the nucleus is greatly exaggerated so that its components are visible. There are six protons (pictured blue) and six neutrons (orange) in the nucleus. The positive charge of the nucleus is compensated by six electrons, arranged into two groups, called shells (two in the innermost shell and four in the next)

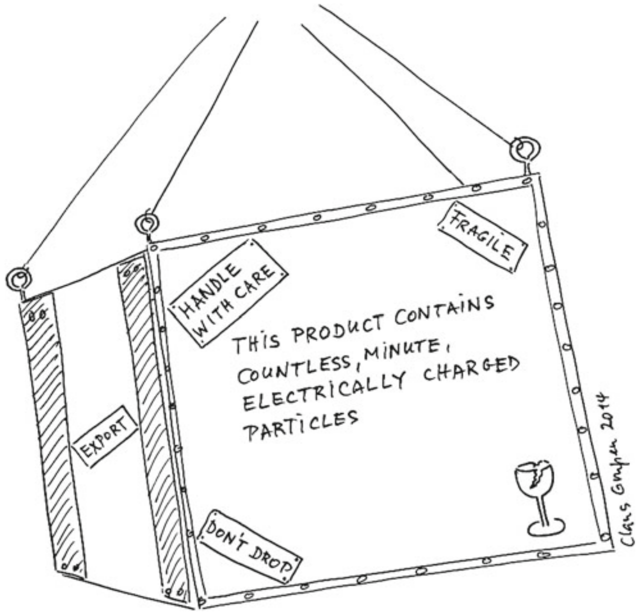
$10^{-6}$). We will also frequently use the power prefixes, shown in Table 2.1. Some of these will be familiar to most readers, perhaps in forms like kilograms (1 000 g), Gigabytes (1 000 000 000 bytes) and millimetres (0.001 m).[2]

Let us rewrite the sizes of the atom and the nucleus in these ways: an atom is typically $10^{-10}$ m or 0.1 nm across, and the nucleus at its centre is more like $10^{-15}$ m or 1 fm wide.

**Table 2.1** Power prefixes for units

| Prefix | Abbreviation | Power of ten | Number |
|---|---|---|---|
| Tera | T | $10^{12}$ | 1 000 000 000 000 |
| Giga | G | $10^{9}$ | 1 000 000 000 |
| Mega | M | $10^{6}$ | 1 000 000 |
| kilo | k | $10^{3}$ | 1 000 |
| milli | m | $10^{-3}$ | 0.001 |
| micro | µ | $10^{-6}$ | 0.000 001 |
| nano | n | $10^{-9}$ | 0.000 000 001 |
| pico | p | $10^{-12}$ | 0.000 000 000 001 |
| femto | f | $10^{-15}$ | 0.000 000 000 000 001 |

[2] A word of caution is in order here: in the USA and most other parts of the world, a billion is $10^9$ while in some parts, including Germany and other European countries, a billion is $10^{12}$. This book will follow the US convention when writing numbers as words.




The nucleus and the surrounding electrons are charged objects. This charge ("electric charge", in full) means that they can interact with electromagnetism, and indeed the nucleus and the electrons are bound together by their mutual electromagnetic attraction. It is possible for many atoms to be joined together into a molecule: these are bound together by a residual electromagnetic interaction between the nuclei and the electrons of the different atoms.

The particles of the nucleus are called nucleons, and there are two types: positively charged protons, and neutral neutrons. Protons and neutrons have very similar masses: the neutron is 0.1 % heavier. The number of protons in a nucleus (the proton number) defines the chemical element: that is to say that the chemical behaviour of an atom is completely determined by the number of protons in its nucleus. For a neutral atom, there will be the same number of electrons in orbit as there are protons in the nucleus. If there are more or fewer electrons than there are protons, there will be a net charge: the atom is then called an ion.

The neutrons are essential in binding the nucleus together, and the number of them is called the neutron number. The *atomic mass* is the number of nucleons in that nucleus, and so is the sum of the proton and neutron numbers. It is possible for different nuclei to have the same proton number, i.e. to be the same element, but to have different numbers of neutrons. For example, all atoms of oxygen have 8 protons, but different atoms of oxygen might have 7, 8, 9 or 10 neutrons (oxygen atoms with 8 neutrons are by far the most common type). These different types of atoms, of the same element but with different numbers of neutrons, are called isotopes. Isotopes which are radioactive are called radioisotopes. Of the four isotopes of oxygen mentioned above, the first is a radioisotope, and the other three are stable (non-radioactive) isotopes.

In this book, two different notations are used to refer to isotopes. The first is a longer form, which is the element name followed by the atomic mass: for example carbon-12 or oxygen-18. In a more shorthand form, isotopes will often be referred to using the notation $^{\text{Atomic mass}}_{\text{Proton number}}$Element. The elements are written using their standard abbreviations: these are usually intuitive (like H for hydrogen and Al for aluminium) but some are not obvious, so a periodic table is given at the back of the book, listing all the elements with their abbreviations. Since the name of the element and the proton number are effectively the same piece of information, that number is often left out, so caesium-137 can be written $^{137}_{55}$Cs or $^{137}$Cs.

Within any nucleus,[3] there are several positively charged protons in close proximity, so one might naturally expect them to fly apart, given the (electromagnetic) repulsion between them. Fortunately for us, there is a force which is about 100 times stronger, rather unimaginatively called the strong nuclear force, which acts to bind a nucleus together. In the same way that the electromagnetic force is carried by photons (particles of light), the strong force is carried by gluons, which are hard to observe directly as they are confined within a nucleus.

Protons and neutrons are themselves composite objects which consist of quarks (see Figure 2.2). These quarks are bound together by the strong nuclear force. Then, just as the different atoms in a molecule are bound together by a residual electromagnetic force, the different nucleons in a nucleus are bound together by a residual strong nuclear force.

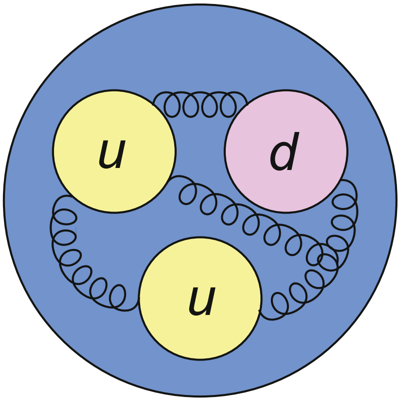
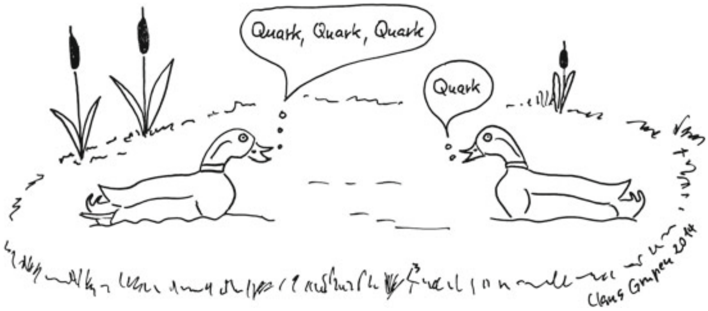



**Fig. 2.2** A proton. Each proton contains three quarks (two of type “up” and one of type “down”), and multiple gluons, shown here as spring-shaped lines, gluing them together. The neutron has the same structure, but two of its quarks are of the “down” type and one is of the “up” type. Quarks have electric charge: “up” quarks have $+\frac{2}{3}$ of a unit and “down” quarks have $-\frac{1}{3}$

[3]With one exception: hydrogen nuclei, by definition, contain only one proton.




*Well, that's one way to remember the word*

## 2.1 Radioactivity

The binding of nucleons in a nucleus is stronger for some isotopes than others, i.e. some nuclei are sufficiently tightly-bound that they are stable, others have weaker binding, and would be in a more tightly-bound configuration if they changed their form: these are the unstable isotopes, which undergo radioactive decay. When we have a group of unstable nuclei of the same type, they will tend to decay, and it is useful to think of the half-life, which is the time taken for half of the nuclei to decay. This is explained in Section 2.2.

Figure 2.3 is a plot of proton number against neutron number. The combinations of numbers of protons and neutrons which make stable nuclei fall into a band called the *valley of stability*. Nuclei which have numbers of protons and neutrons which put them inside this band are likely to be stable, and moving further from the valley in either direction, the nuclei become ever more unstable (i.e. have shorter half-lives). The plot shows that, for stable nuclei of lighter elements, there are approximately as many protons as neutrons. For heavier elements, there are more neutrons than protons.

Protons, to the best of our knowledge, are stable.[4] Free neutrons, i.e. ones outside a nucleus, are not stable: they have a half-life of about 10 min. They decay into a proton and an electron (and an antineutrino, written $\overline{\nu}$, which is a very light, neutral particle[5]). This decay can be written as the equation:

$$n \rightarrow p + e^- + \overline{\nu}\,.$$

[4]Experiments are underway to find out if the proton is completely stable, or merely has an enormous half-life. The current limit says that the half-life of the proton is something over $10^{29}$ years, vastly longer than the age of the universe (13.8 billion years).

[5]There are in fact three types of neutrino, and three corresponding types of antineutrino, as explained in the glossary, but that is not important here.

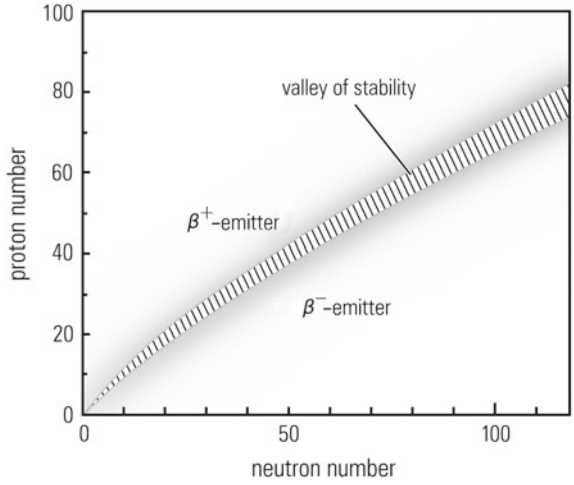



**Fig. 2.3** Neutron-to-proton ratio for stable nuclei ($\beta^-$ particles are electrons and $\beta^+$ are positrons)

In a nucleus with excess neutrons (see Figure 2.3), the same process can occur for one or more of the neutrons, and in this case the proton stays in the nucleus, and the electron is emitted. This emitted electron is referred to as a $\beta^-$, pronounced "beta minus", and the nucleus as a $\beta^-$-emitter.

Similarly, it is possible for nuclei with excess protons to be $\beta^+$-emitters. In this case, a proton decays into a neutron by emitting a positron ($\beta^+$), which is like an electron but positively charged, and a neutrino (this kind of decay is only possible inside an unstable nucleus: free protons cannot decay). However, there are two further possibilities for a nucleus with excess protons: $\alpha$ decay, which is discussed later in this section, and electron capture. In electron capture, one of the orbiting electrons is absorbed by one of the protons in the nucleus, leaving a neutron (and causing the emission of a neutrino).[6]

The difference between a $\beta^-$ and a $\beta^+$, between electron and positron, is an important one in all of particle and nuclear physics. The electron and positron are each other's antiparticles: they are particles identical in all ways (such as their masses, stabilities and the absolute size of their charges) except they are of opposite charge. All particles have antiparticles, although for some, such as the photon, the antiparticle is the same as the particle.

The original (*parent*) nucleus and the resulting (*daughter*) nucleus have certain specific energies. This means that the $\beta$ decay between them will give off a certain, specified amount of energy. However, because this energy is shared between the two emitted particles (electron and antineutrino, or positron and neutrino), there is a range of possible $\beta$ particle energies, up to a certain maximum energy. In this maximum case, the $\beta$ particle is taking all the energy, and the (anti)neutrino effectively none.

[6]This combination of a proton and electron into a neutron is exactly what happens when the dense core of a star is collapsing after a supernova explosion, and leads to the formation of a neutron star.


After a $\beta$ decay, the daughter nucleus is often not in the most stable arrangement for that nucleus: it is in an *excited state*.[7] Excited states are marked in this book with an asterisk (*). These states move to the most stable (*ground*) state by emitting $\gamma$ (pronounced "gamma") rays. These $\gamma$ rays are photons (particles of electromagnetic radiation) of high energy. They are therefore physically the same phenomenon as light, but with dramatically higher frequency and tiny wavelength. It is normal for people to think of light as a wave, but it can equally be thought of as a particle, and these descriptions do not contradict each other. In this book, the particle description is the more useful one.

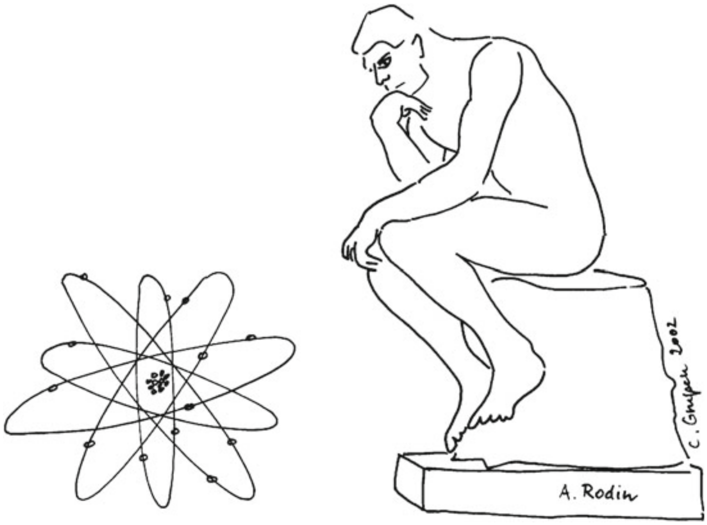
Since the energy difference between the excited nucleus and the ground state is fixed, these $\gamma$ rays have a single, defined energy for each transition, rather than the continuous range described above for $\beta$ particles.

When thinking about the energy of a single particle, or the average energy of a group of particles, it is useful to have a very small unit of energy, which is of roughly the scale of the energy carried by individual particles. The most common unit for this in particle and nuclear physics is a funny little unit called the electron-Volt (eV), whose origin is explained in Chapter 5. This unit, about $1.6 \times 10^{-19}$ Joules, is so small that it would take several billion electron-Volts to lift up a grain of sand by one centimetre! In an old-fashioned TV set, each electron is accelerated up to an energy of about 20 keV.

As an example for $\beta$ decays let us consider the decay of caesium-137:

$$\begin{aligned} {}^{137}_{55}\mathrm{Cs} \rightarrow {}^{137}_{56}\mathrm{Ba}^* &+ e^- + \overline{\nu} \\ \hookrightarrow\ & {}^{137}_{56}\mathrm{Ba} + \gamma \,. \end{aligned}$$

[7]Imagine a pile of rocks in which one of the rocks in the middle was suddenly made smaller. The pile would probably want to resettle, as do nuclei after this kind of change.




© by Claus Grupen

*The thinker (about nuclear physics)*

The $^{137}$Cs gives off an electron of energy up to 514 keV, and leaves an excited nucleus of barium-137. That excited nucleus ($^{137}$Ba*) then decays, giving off a $\gamma$ ray (which always has the energy 662 keV). In fact, it is also possible for this process to skip the excited state, and go straight to the barium's ground state, so no photon is emitted and there is more energy for the electron and antineutrino. This happens 5 % of the time.

The excited state of a nucleus will typically last for only a small fraction of a second (maybe $10^{-11}$ s) before decaying. Some nuclear excited states, however, last much longer. This excited state of barium-137 is an example: its half-life is two and a half minutes. These relatively long-lived nuclear excited states are called *metastable* states, and can be marked with a superscript "m", for example $^{137\mathrm{m}}$Ba.

Heavy nuclei, i.e. those containing a large number of nucleons, tend to decay by the emission of an $\alpha$ (pronounced "alpha") particle. This particle is composed of a pair of protons and a pair of neutrons, and is the same as the nucleus of a helium atom. This grouping of four nucleons happens to be a particularly stable and low-energy scenario, so this type of decay is usually preferred where it is possible, given the energies of the parent and daughter nucleus. This means that, where this decay and $\beta^+$ decay are both possible (which is frequently the case), it is usually $\alpha$ decay which takes place.

An example of an $\alpha$-emitter is uranium-238, which gives out an $\alpha$ particle and transforms into excited states of thorium-234:

$$^{238}_{92}\mathrm{U} \rightarrow {}^{4}_{2}\alpha + {}^{234}_{90}\mathrm{Th}^* \, .$$

Since the nuclear levels have certain fixed energies, and only one particle is being given off in the decay, the emitted $\alpha$ particles from a particular isotope all have a single, characteristic energy, in the same way that $\gamma$ rays from excited nuclei do.

One last possibility for the decay of heavy nuclei (for proton numbers over 90) is spontaneous fission. This is the process in which the nucleus splits into two lighter nuclei which are of broadly similar size, for example, californium-252 can fission into barium-148 and molybdenum-104:

$$^{252}_{98}\text{Cf} \rightarrow {}^{148}_{56}\text{Ba} + {}^{104}_{42}\text{Mo} \ .$$

In the earlier discussion on the valley of stability, the plot showed that heavier nuclei have proportionally more neutrons than lighter ones. This means that, after a fission, there will be an excess of neutrons, because the smaller nuclei created will still have proportionally as many neutrons as their larger parent. Usually, some of this imbalance is countered by the emission of free neutrons during the fission process (*prompt neutrons*), for example, four prompt neutrons are given out in the fission of fermium-256 to palladium-112 and xenon-140:

$$^{256}_{100}\text{Fm} \rightarrow {}^{112}_{46}\text{Pd} + {}^{140}_{54}\text{Xe} + 4n \ .$$

Frequently, there is still an imbalance in the fission products, so they will either undergo $\beta$ decay, or give off neutrons directly (*delayed neutrons*), or both.

There are some isotopes which do not fission spontaneously, but can undergo *induced* fission if they are struck by one of these emitted neutrons. An example is the induced fission of $^{235}_{92}\text{U}$, given by the reaction

$$^{235}\text{U} + n \rightarrow {}^{236}\text{U}^* \rightarrow {}^{139}\text{I}^* + {}^{96}\text{Y}^* + n \ .$$

There is one prompt neutron, and then (not shown in the reaction above) the highly excited iodine and yttrium nuclei will also emit a neutron each, and also undergo several $\beta^-$ and $\gamma$ decays to reach stable nuclear configurations.

In this example, a single free neutron was introduced, and then one prompt neutron and two delayed neutrons were emitted. The emitted neutrons can then go on and induce further fissions, and by continuing in this way, an increasing, or at least self-sustaining, chain reaction can be built up. This is the basis for both fission bombs and all currently operational nuclear power stations (see Chapters 8 and 9).

An excited nucleus left after a decay can release its energy in an indirect way: although normally it will release its excess energy by $\gamma$ emission, it is also possible for this excitation energy to be transferred directly onto one of the electrons orbiting the nucleus: this electron will then leave the atom. These emitted electrons are called *conversion electrons*. However, the emissions need not stop there. The electron will leave a vacancy in its orbit (as will one taken in an electron capture), and one of the other orbiting electrons will fall in, releasing some energy. This energy can then be given out as an X ray, as shown in Figure 2.4.

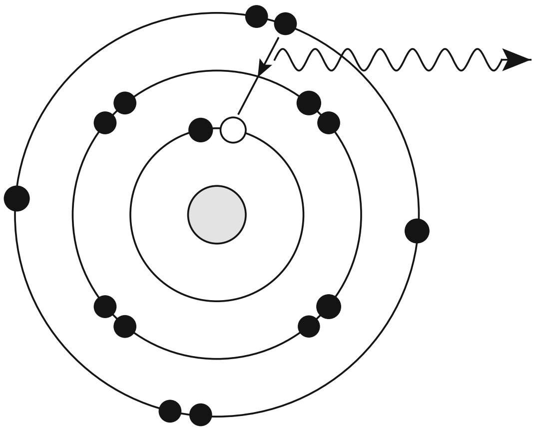


**Fig. 2.4** Illustration of the production of characteristic X rays. An electron has been removed from the atom (empty circle) and one from a higher shell moves down, emitting an X ray of characteristic energy (the energy difference between the shells)

The most important properties of the different types of radiation mentioned in this chapter are compiled in Table 2.2. They are often referred to as *ionising radiation*, as they can produce ions from atoms when they interact, by removing electrons from them. This is explained in Section 3.1. It is worth noting that all these types of ionising radiation can be referred to as rays or as particles, and in this book, these terms are used interchangeably.

The X rays listed in the table deserve further explanation, as they are very relevant in the field of radiation protection. X rays are very short-wavelength electromagnetic radiation similar to $\gamma$ radiation, but of slightly lower energy (longer wavelength). They are produced by the movements of charged objects: either during the transition of an electron between shells in an atom, or during the deceleration of a particle in an electric field (which can be within a material). X rays are discussed in more detail later in this book (see Chapter 5).

**Table 2.2** Some properties of different types of ionising radiation

| Type of radiation | Emitted particle | Typical energy |
|---|---|---|
| $\alpha$ ray | ${}^4_2$He | 5 MeV |
| $\beta^-$ ray | $e^-$ | 1 MeV |
| $\beta^+$ ray | $e^+$ | 1 MeV |
| $\gamma$ ray | $\gamma$ | 1 MeV |
| Neutron | $n$ | 1–6 MeV |
| X ray | $\gamma$ | 100 eV – 100 keV |

## 2.2 Activity and Half-Life

The number of radioactive decays in a particular time is called the activity, and is measured in Becquerels (Bq). 1 Bq is one decay per second. The old unit Curie (Ci) is a very large unit, corresponding to the activity of 1 gram of radium-226:

$$1\,\mathrm{Ci} = 3.7\times 10^{10}\,\mathrm{Bq} = 37\,\text{billion}\,\mathrm{Bq}$$

$$1\,\mathrm{Bq} = 27\times 10^{-12}\,\mathrm{Ci} = 27\,\text{pico-Curie}.$$

1 Bq is a very small activity. The human body typically has an activity of 9000 Bq (about 100 Bq per kg), which essentially originates from radioactive potassium ($^{40}$K) and radioactive carbon ($^{14}$C), which are predominantly ingested from normal food.

In radioactive decays, the number of nuclei decaying in a particular time is directly related to the number of existing nuclei. The number of radioactive nuclei decreases as the decay progresses, so the rate of decays will slow as time goes on. The decrease in the number of radioactive nuclei depends on the type of nucleus (isotope): each one has a half-life, which describes its rate of decay. The half-life indicates the time taken for half of the original nuclei to decay. Then after two half-lives, only one quarter of the original nuclei remain. Half-lives can vary between tiny fractions of a second and billions of years, depending on the specific isotope. Every half-life decreases the number of nuclei by a factor of two, as shown in Figure 2.5. Let us take an example from nuclear medicine: a patient is administered 0.16 nanograms of the radioactive


*The fish on the right has the higher activity. Both fish would breach moderately cautious safety standards.*

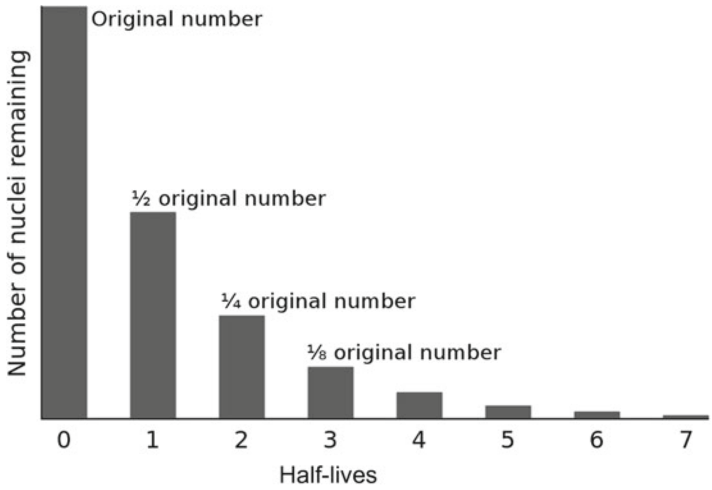



**Fig. 2.5** The radioactive decay law

element iodine-131 (which has a half-life of 8 days) for the diagnosis of a possible thyroid cancer. Then after 32 days (4 half-lives), the amount of iodine-131 will have halved four times, i.e. one sixteenth of the original amount will remain, namely 0.01 ng. Only for very long times will the amount of iodine-131 approach zero.

Just as the number of radioactive nuclei decays in time, so does the activity. In our earlier example, the iodine-131 starts with an activity of 740 kBq, and after 32 days, the activity is about 46 kBq. Radioactive sources with a large half-life naturally have lower activities for a given number of nuclei. Frequently it is said that long-lived radioactive waste (e.g. with a half-life of a million years) is dangerous, because it has to be stored safely for this long period. This is not the whole story, because the long half-life means that the decay rate is rather low, so the immediate risk from these long-lived isotopes is relatively small.

## 2.3 Radiation Doses

Understanding the activity in Becquerels is the first step to finding out about any possible biological effects, but does not tell us a great deal by itself. This is because, apart from the absolute amount of energy absorbed in the body, the biological effects are related to:

**the size of the exposed area or body** – for the same absolute amount of radiation, a larger body will feel less effect, so the measures of radiation exposure must be inherently about the exposure per kilogram of tissue.

**the radiation type** – some types of radiation are intrinsically more damaging than others.

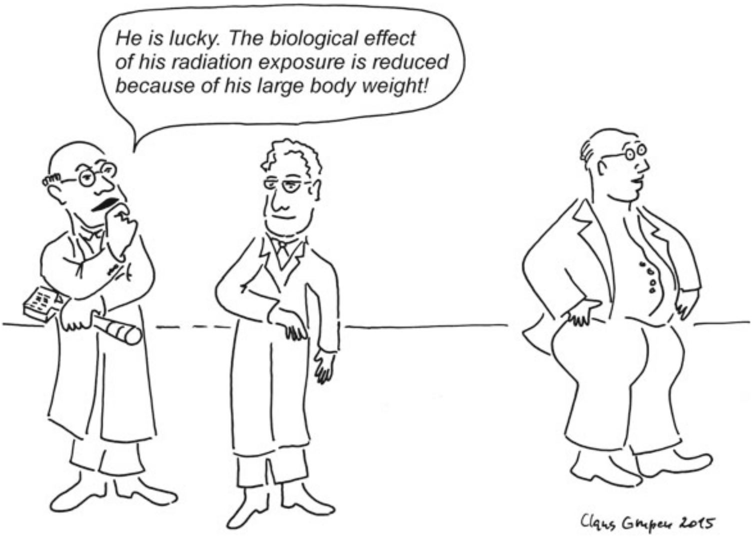
**the distribution of the dose** – some tissues of the body are more sensitive to radiation than others.

In this section, the units taking account of each of these factors in turn will be discussed. Starting with the amount of energy absorbed, the *energy dose* (measured in Grays (Gy)) is worked out by looking at the exposure per kilogram. Then the *equivalent dose* (measured in Sieverts (Sv)) is worked out by also taking account of the radiation type. Finally, the *effective dose* (also measured in Sv) is found by additionally taking account of the different tissues exposed. This last measure takes account of all the effects, and is the standard measure used in this book. Later in this book, when talking of a "dose", this effective dose is what is meant.

The energy dose is the amount of energy absorbed per unit mass. Because energy is measured in Joules, and mass is measured in kilograms, it is possible to talk of this quantity in Joules per kilogram. In this context, one Joule per kilogram is called one Gray (Gy). The old unit rad (radiation absorbed dose), still in use in the United States, is one hundredth of a Gray.

Apart from these units, another quantity can be used for the amount of charge created by radiation, the Roentgen (R). This rather specialised unit is sometimes still used in medicine. 1 Roentgen is equivalent to 8.8 mGy.

The Gray, the rad and the Roentgen describe the pure physical energy absorption. These units cannot easily be translated into the biological effect of radiation. As explained in Chapter 3, some radiation types have a more concentrated effect than others. Electrons, for example, ionise relatively weakly while, by contrast, $\alpha$ rays



give a high ionisation density, which means more concentrated damage. Therefore, the normal biological repair mechanisms are less likely to be effective after damage caused by $\alpha$ rays.

### 2.3.1 Weighting Factors

In order to take account of the biological effectiveness of each radiation type, the *radiation weighting factors* are used. The energy dose is multiplied by the relevant radiation weighting factor to find the equivalent dose for a particular radiation type. The equivalent dose is measured in Sievert (Sv). The old unit rem (roentgen equivalent man), still in use in the US, is one hundredth of a Sievert.

The radiation weighting factors depend on the type of radiation and for neutrons also on their energy. The definition of radiation weighting factors, following the recommendation of the International Commission on Radiological Protection (ICRP), is given in Table 2.3. The table also mentions muons: these are short-lived particles which are produced by cosmic radiation (see Chapter 6).

As an example, let us assume that a radiation worker in a reprocessing plant is accidentally exposed to an energy dose of 20 mGy from $\alpha$ particles, and one of 50 mGy from $\gamma$ radiation. Then his equivalent dose is given by the sum of these energy doses with their weighting, i.e. by $(20\,\text{mGy} \times 20 + 50\,\text{mGy} \times 1)\,\text{mSv} = 450\,\text{mSv}$. This is quite a significant dose, because the lethal dose of radiation for humans is 4000 mSv (the lethal dose is the one giving a death rate of 50 % within a month).

In many cases, particularly when dealing with exposures caused by specific events (such as the taking of an X-ray image), a person will have an exposure which is limited to one region of the body. In these cases, there is often a significant dose (remembering this is a per-kilogram measure) for one tissue, and a small or irrelevant dose for other parts of the body. In such cases, it is necessary to convert the partial-body dose into a whole-body dose, to understand the extent of the damage. For this, a tissue weighting factor has to be assigned to the irradiated organs of the body. This effective dose (also known as the effective dose equivalent) is obtained by multiplying the partial-bodydose received with the corresponding tissue

**Table 2.3** Radiation weighting factors

| Type of radiation | Factor |
|---|---|
| $\gamma$ and X rays, all energies | 1 |
| Electrons and muons, all energies | 1 |
| Neutrons, energy under 10 keV | 5 |
| Neutrons, energy 10–100 keV | 10 |
| Neutrons, energy 100 keV–2 MeV | 20 |
| Neutrons, energy 2–20 MeV | 10 |
| Neutrons, energy over 20 MeV | 5 |
| Protons, all energies | 2 |
| $\alpha$ particles, fission fragments, heavy nuclei | 20 |

**Table 2.4** Tissue weighting factors

| Organ or tissue | Factor |
|---|---|
| Red bone marrow | 0.12 |
| Colon | 0.12 |
| Lung | 0.12 |
| Stomach | 0.12 |
| Chest | 0.12 |
| Gonads | 0.08 |
| Bladder | 0.04 |
| Liver | 0.04 |
| Oesophagus | 0.04 |
| Thyroid gland | 0.04 |
| Periosteum (bone surface) | 0.01 |
| Skin | 0.01 |
| Brain | 0.01 |
| Salivary glands | 0.01 |
| Other organs or tissue | 0.12 |

weighting factor for the organ in question. If more than one organ is concerned, one has to sum up the various contributions by multiplying the partial-body doses with the appropriate tissue weighting factors. The tissue weighting factors are given in Table 2.4.

For the purposes of radiation protection it is simply defined that the human body has fourteen 'organs' (and one further category for everything else). The tissue weighting factors are scaled so that their total is 1, and so they can be thought of as the percentage importance of that part of the body with respect to radiation damage. The thyroid typically weighs about 20 g, or 0.03 % of bodyweight, but its tissue weighting factor is 0.04, i.e. from a radiation damage point of view, it has an importance of 4 %, because it is so sensitive to radiation. In contrast, "other organs and tissue" is usually over 70 % of the bodyweight, but has only 12 % importance because it does not include any organs with high sensitivity to radiation.

The object of this calculation is that a non-uniform irradiation of the body with a particular effective dose should bear the same radiation risk as a homogeneous whole-body irradiation with an equivalent dose of the same size.

To give an example: a radiation worker has collected a broken radioactive source with his bare hands (skin dose 20 mSv), which he should not have done, and carried it in his lab coat pocket (5 mSv each for the lung and chest). The effective dose is then worked out to be $(20 \times 0.01 + 5 \times 0.12 + 5 \times 0.12)\,\text{mSv} = 1.4\,\text{mSv}$.


"Atomic progress is quite educating!"

after Jupp Wolter

If a dose is restricted to a particular part of the body, then naturally, the effective whole-body dose that is calculated from it will have a smaller headline number. This can be important in understanding the scale of the dose. For example, let us imagine a partial-body dose of 4 Sv has been applied to the brain of a patient for cancer treatment, with no exposures for any other tissues. This looks initially like the procedure has administered a lethal dose, until we realise that the number given is not an effective whole-body dose, but a localised one. The effective dose here is 40 mSv (because the weighting factor for the brain is 0.01). This is still a significant dose, and would not be administered lightly, but it would not be lethal.

In principle, it is important to consider further radiation-relevant factors such as an increase in the risk of an additional dose after a high first dose, or reduced biological effects from an irradiation split into several separate doses.[8] This technique of intermittent radiation is used in cancer therapy: if a patient needs to receive, say, an effective dose of 2 Sv to destroy a tumour, this dose might be applied in ten separate fractions of 0.2 Sv, because in the intervals between these fractions, the healthy tissue will recover more easily than the cancerous tissue will. A typical interval between subsequent fractions of irradiation is a day.

To consider the time dependence of a dose, we use the *dose rate*: the change of the dose in a particular time interval. The dose rate may change rapidly, particularly for radioactive sources with short half-lives. A typical dose rate due to normal environmental radiation for humans is 0.3 $\mu$Sv per hour.

[8] Historical attempts to do this have led to the measures Relative Biological Effectiveness (RBE) and Quality factor, which we do not consider further here.

### *2.3.2 Avoiding Doses*

It makes sense intuitively that being more distant from a source of radiation reduces the dose received from it. Indeed, just from the spreading out of the radiation, for most sources, the intensity falls with the square of distance (the exception being when the source is directed, as it is in an X-ray tube). This means that being twice as far away from a source reduces the dose by a factor of four. In addition, the intensities of $\alpha$ and $\beta$ rays are reduced significantly even by a few centimetres of air, due to absorption (see Chapter 3). This means that the dose received falls markedly with increasing distance from the source.

To avoid unnecessary doses, it is important to remember some simple rules for the handling of radioactive sources:

- keep the activity of the source as low as reasonable,
- keep a sufficient distance away from the radioactive material, if possible,
- keep the exposure time as short as feasible, and
- use shielding whenever possible.

Every person, whereever he or she is in the world, is exposed to natural radioactivity from cosmic radiation, terrestrial radiation, incorporation (ingestion (eating and drinking) and inhalation (breathing)), and the activity of his or her own body. This number averages about 2.5 mSv per year, but varies a little depending on where the person lives. Higher values occur in areas where radioactive elements occur in the soil (e.g. radioactive thorium). Additional radiation, for example due to nuclear power plants or other technical installations, is limited by most national regulations to 1 mSv per year. This chapter ends with an extra section about putting this kind of dose into context.

## Summary

Ionising radiation is released in most nuclear transformations. $\alpha$ rays are helium nuclei. $\beta$ sources emit high-energy electrons ($\beta^-$) or their antiparticles ($\beta^+$, called positrons). $\alpha$ and $\beta$ decays alter the chemical nature of an element. $\gamma$ rays, which are high-energy photons, are often emitted by a nucleus after $\alpha$ or $\beta$ decay. Fission (spontaneous or induced) is also possible, and the neutron excess in fission products can be reduced by prompt or delayed neutron emission, or by $\beta^-$ decays. The essential units of radiation protection are the Becquerel (Bq) for the activity and the Sievert (Sv) for the effective dose (which includes weightings for the biological effectiveness). This is fundamentally a per-kilogram measure, because a larger person will be able to absorb a larger absolute amount of radiation for the same amount of damage. Each radioactive isotope has a particular half-life. Radioisotopes with large half-lives are associated with a low activity, and those with short half-lives with a high one. The dose from a source can be reduced by keeping a distance from it, reducing the exposure time, and using shielding.

## Putting doses in context

The common units for radiation doses, such as Sv, can be hard for the layman to interpret. Even low radiation exposures, which can only be detected by extraordinarily sensitive measurement devices, occasionally lead to over-reactions in public discussions. It is very important to express radiation levels, caused, for example, by the transport of nuclear waste (see Chapter 12), or by nuclear power plants, in units which can be understood and interpreted by the layman. What the public needs is a good sense of scale, so that the general size of particular radioactive exposures can be understood in context.

Mankind has evolved and developed alongside perpetual natural radiation, and there are no hints whatsoever that this radiation has created any problems for our biology. The natural radiation dose is subject to regional variations, but the natural annual whole-body radiation dose does not fall below 2 mSv for anybody (it is several times higher than this in some places). This natural annual dose sets the scale on which to judge on additional man-made radiation burdens, for example, during medical diagnosis.

This 2 mSv annual minimum should provide the reader with a useful yardstick for the scale of doses discussed in this book and elsewhere. It should be a sufficiently simple and memorable number, so that anyone of any background can make a realistic, informed judgment about radiation risks. Some typical examples are provided below.

| Type of radiation exposure | Dose in mSv | Years of minimal background dose |
|---|---|---|
| Eating one normal banana | 0.0001 | 0.00005 |
| Dental X-ray image | 0.01 | 0.005 |
| Annual exposure to the public from nuclear power plants | under 0.02 | under 0.01 |
| Worker transporting radioactive waste | under 0.03 | under 0.015 |
| Flight from London to New York | 0.03 | 0.015 |
| X-ray image of the chest | 0.03 | 0.015 |
| Mammography | 0.5 | 0.25 |
| Scintigraphy of the thyroid gland | 0.8 | 0.4 |
| Annual dose for heavy smoker | 1 | 0.5 |
| Positron-emission tomography (PET) | 8 | 4 |
| Computed tomography (CT) of the chest | 10 | 5 |
| Annual limit for exposed workers<br>in Europe<br>in the USA | <br>20<br>50 | <br>10<br>25 |
| Maximum lifetime dose for exposed workers in Europe | 400 | 200 |
| Lethal dose | 4000 | 2000 |

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