Radioactivity

At the end of the nineteenth century and in the early part of the twentieth, it was discovered, mainly due to the work of Henri Becquerel and Marie and Pierre Curie, that some nuclei are unstable. That is to say, nuclei spontaneously emit a particle or particles, they decay, and become different nuclei. This phenomenon is called radioactivity. It was soon realized that three distinct emissions take place, called alpha, beta and gamma radiations.

Objectives

By the end of this chapter you should be able to:

- describe the properties of *alpha, beta* and *gamma* radiations;
- explain why some nuclei are *unstable* in terms of the relative number of neutrons to protons;
- define *half-life* and find it from a graph;
- solve problems of *radioactive decay*.

The nature of alpha, beta and gamma radiations

Early experiments with radioactive sources confirmed that three separate kinds of emissions took place. Called alpha, beta and gamma radiations, or particles, these emissions could be distinguished on the basis of their different ionizing and penetrating power.

Ionization

Alpha, beta and gamma radiations ionize air as they pass through it; this means they knock electrons out of the atoms of the gases in the air. An alpha particle of energy 2 MeV will produce about 10 000 ion pairs per mm along its path in air. A beta particle of the same energy will only produce about 100 ion pairs per mm in air. A gamma ray will produce about one ion pair per mm.

By letting these **ionizing radiations** pass through regions of magnetic (or electric) fields, it was seen that two of the emissions were oppositely charged and the third electrically neutral (see Figure 2.1).

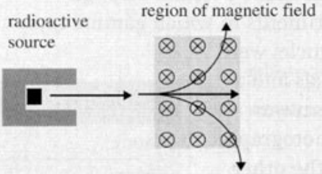

Figure 2.1 The existence of three distinct emissions is confirmed by letting these pass through a magnetic field and observing the three separate beams.

Alpha particles

The positive emissions were called alpha particles and were soon identified as nuclei of helium in an experiment by Rutherford and Rhoyd. By collecting the gas that the alpha particles produced when they came in contact with electrons and analysing its spectrum, its properties were found to be identical to those of helium gas. Thus, the alpha particles have a mass that is about four times the mass of the hydrogen atom and an electric charge equal to $+2e$.

Beta particles

The negative emissions (beta particles) were identified as electrons (charge $-e$) by experiments similar to Thomson's e/m experiment, which measured the charge-to-mass ratio. (Actually, the measured charge-to-mass ratio for the beta particles decreased slightly from the standard value as the speed of the betas increased. This is consistent with the theory of special relativity, which states that the mass of an object increases as the speed becomes comparable to the speed of light. This was an early test of the theory of relativity.)

Gamma rays

The electrically neutral emissions are called gamma rays and are photons (just like the photons of ordinary electromagnetic radiation) with very small wavelengths. Typically these wavelengths are smaller than 10^{-12} m, which is smaller than X-ray wavelengths. This identification was made possible through diffraction experiments in which gamma rays from decaying nuclei were directed at crystals and a diffraction pattern was observed on a photographic plate placed on the other side of the crystal.

Absorption

Alpha particles are the easiest to absorb. A few centimetres of air will stop most alpha particles (see Figure 2.2). Beta particles will be stopped by a few centimetres of paper or a thin sheet of metal (a few millimetres in thickness) while gamma particles will easily penetrate metallic foils; if they are energetic enough they will be stopped only by many centimetres of lead.

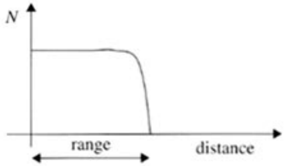

Figure 2.2 The penetration of matter by alpha particles of a fixed energy. The number of particles transmitted falls sharply to zero after a distance called the range. Particles of higher energy will have a larger range.

Further studies show that alpha particles have specific energies, whereas beta particles have a continuous range of energies. Gamma rays from a particular nucleus also have a few discrete values with maximum energies of about 1 MeV or so. Alphas are rather slow (about 6% of the speed of light) whereas betas are very fast (about 98% of the speed of light). Gammas, being photons, travel at the speed of light. These findings are summarized in Table 2.1.

Characteristic	Alpha particle	Beta particle	Gamma ray
Nature	Helium nucleus	(Fast) electron	Photon
Charge	$+2e$	$-e$	0
Mass	6.64×10^{-27} kg	9.1×10^{-31} kg	0
Penetrative power	A few cm of air	A few mm of metal	Many cm of lead
Ions per mm of air for 2 MeV particles	10 000	100	1
Detection	Causes strong fluorescence	Causes fluorescence	Causes weak fluorescence
	Affects photographic film	Affects photographic film	Affects photographic film
	Is affected by electric and magnetic fields	Is affected by electric and magnetic fields	Is not affected by electric and magnetic fields

Table 2.1 Properties of alpha, beta and gamma radiations.

Detecting radiation

One way to detect radiation is to take advantage of their ionizing effect. In the Geiger–Müller (GM) tube (Figure 2.3), radiation enters a chamber through a thin window. The chamber is filled with a gas, which is ionized by the incoming radiation. The positive ions accelerate toward the earthed casing and the electrons toward the positive electrode (kept at a few hundred volts) and so more ions are created as a result of collisions with the gas molecules. This registers as a current in the counter connected to the GM tube. The counter can also turn the current into an audible sound, giving a 'click' whenever an ionizing particle enters the tube.

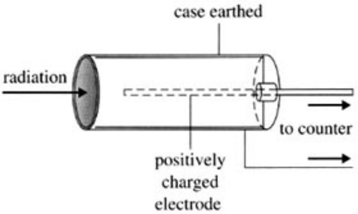

Figure 2.3 A Geiger–Müller tube for detecting ionizing radiation.

Segre plots

There are about 2500 nuclides (nuclei with a specific number of protons and neutrons), but only about 300 of them are stable; the rest are unstable (i.e. radioactive). Figure 2.4 is a plot of neutron number versus proton number (called a Segre plot) for the stable nuclei. The straight line corresponds to nuclei that have the same number of protons and neutrons. The plot shows that stable nuclei have, in general, more neutrons than protons. As the number of protons in the nucleus increases, the electrostatic repulsion between them grows as well, but the strong nuclear force does not grow proportionately since it is a short-range force. Thus, *extra* neutrons must be put in the nucleus in order to ensure stability through an increased nuclear force without participating in the repulsive electric force. (On the other hand, *too many* neutrons will also make the nucleus unstable by energetically favouring decays of neutrons into protons – hence there is a limit as to how large a nucleus can get).

A similar principle is also used in the *ionization chamber.* Gas contained in the chamber is ionized by incoming radiation and the current so produced is a measure of the amount of radiation entering the chamber.

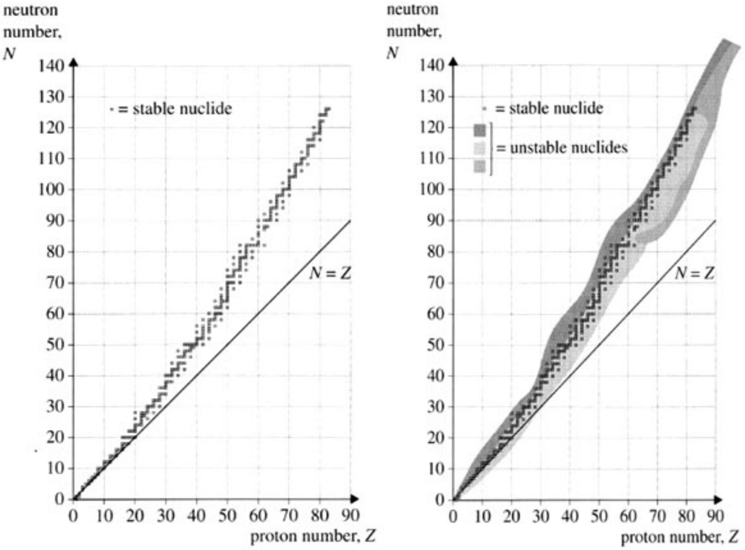

Figure 2.4 A Segre plot of stable nuclides.

Radioactive decay equations

Alpha decay

An example of alpha decay is that of uranium decaying into thorium:

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

We say that the nucleus of uranium, being unstable, decayed into a nucleus of thorium and a nucleus of helium. Helium nuclei, being much lighter than thorium, actually move away from the uranium nucleus with a certain amount of kinetic energy. The energy of the alpha particle emitted can be either one specific value or a series of specific energy values (a discrete spectrum of energies). Note that in the reaction representing this decay, the total atomic number on the right-hand side of the arrow matches the atomic number to the left of the arrow. The same holds also for the mass number. This is true of all nuclear decays. Other examples are

$$^{224}_{88}\mathrm{Ra} \rightarrow {}^{220}_{86}\mathrm{Rn} + {}^{4}_{2}\alpha$$

$$^{212}_{84}\mathrm{Po} \rightarrow {}^{208}_{82}\mathrm{Pb} + {}^{4}_{2}\alpha$$

Beta decay

The second example of a radioactive decay is that of beta decay, such as

$$^{234}_{90}\mathrm{Th} \rightarrow {}^{234}_{91}\mathrm{Pa} + {}^{0}_{-1}e + {}^{0}_{0}\bar{\nu}_e$$

Note the appearance of the electron (the beta particle) in this decay. The last particle (the electron antineutrino) is included for completeness and need not concern us further here. Unlike alpha decay, the energy of the emitted beta particle has a continuous range of energy, a continuous spectrum. Note again how the atomic and mass numbers match. This is a decay of a nucleus of thorium into a nucleus of protactinium. Other examples are

$$^{214}_{82}\mathrm{Pb} \rightarrow {}^{214}_{83}\mathrm{Bi} + {}^{0}_{-1}e + {}^{0}_{0}\bar{\nu}_e$$

$$^{14}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} + {}^{0}_{-1}e + {}^{0}_{0}\bar{\nu}_e$$

Gamma decay

The third example of a decay involves the emission of a photon:

$$^{238}_{92}\mathrm{U}^* \rightarrow {}^{238}_{92}\mathrm{U} + {}^{0}_{0}\gamma$$

The star on the uranium nucleus on the left side of the arrow (the decaying nucleus) means that the nucleus is in an excited state, very much like a hydrogen atom in an energy state above the ground state. Nuclei, like atoms, can only exist in specific energy states. There exists a lowest energy state, the ground state, and excited states with energies larger than that of the ground state. Whenever a nucleus makes a transition from a high to a lower energy state, it emits a photon whose energy equals the energy difference between the initial and final energy states of the nucleus. The typical energies of nuclear states are a few million electronvolts (MeV). This means that the emitted photon in a nuclear transition will have an energy of the order of a few million electronvolts and will thus have a wavelength of

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

where ΔE is the photon's energy, h is Planck's constant (6.63×10^{-34} J s) and c is the speed of light. Substituting, say, 1 MeV for this energy, we find $\lambda = 1.2 \times 10^{-12}$ m. In contrast to the photons in atomic transitions, which can correspond to optical light, these photons have very small wavelengths. They are called gamma rays.

The changes in the atomic and mass numbers of a nucleus when it undergoes radioactive decay can be represented in a diagram of mass number against atomic number. A radioactive nucleus such as thorium ($Z = 90$) decays first by alpha decay into the nucleus of radium ($Z = 88$). Radium, which is also radioactive, decays into actinium ($Z = 89$) by beta decay. Further decays take place until the resulting nucleus is stable. The set of decays that takes place until a given nucleus

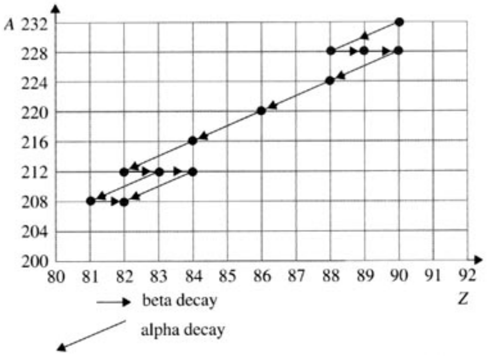

Figure 2.5 The decay series of thorium ($Z = 90$, $A = 232$). One alpha decay reduces the mass number by 4 and the atomic number by 2. One beta decay increases the atomic number by one and leaves the mass number unchanged. The end result is the nucleus of lead ($Z = 82$, $A = 208$).

ends up as a stable nucleus is called the *decay series* of the nucleus. Figure 2.5 shows the decay series for thorium. Successive decays starting with thorium end with the stable nucleus of lead.

Example question

Q1

A nucleus ${}^{A}_{Z}X$ decays by alpha decay followed by two successive beta decays. Find the atomic and mass numbers of the resulting nucleus.

Answer

The decay equation is

$${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z}Y + {}^{4}_{2}\alpha + 2\,{}^{0}_{-1}e$$

so the atomic number is Z and the mass number is $A - 4$.

The law of radioactive decay

We now come to the details of a decay. Suppose we concentrate on the particular decay ${}^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}\alpha$, and that we are given a container with a specific number of atoms of uranium.

▶ The law of radioactive decay states that the number of nuclei that will decay per second (i.e. the rate of decay) is proportional to the number of atoms present that have not yet decayed.

This is a form of a physical law implying a *statistical* or *random* nature. This means that we cannot predict exactly when a *particular* nucleus will decay. But, given a large number of nuclei, the radioactive decay law can be used to predict the number of atoms that will have decayed after a given interval of time. The radioactive decay law leads to an exponential decrease of the number of decaying nuclei. Figure 2.6 shows an example of a radioactive decay in which the initial number of nuclei present is 200×10^{26}. As time passes, the number of undecayed nuclei is decreased. After a certain interval of time (5 s in this example), the number of undecayed nuclei left behind is half of the original number. If another 5 s goes by, the number of undecayed nuclei is reduced by another factor of 2, which is a factor of 4 relative to the original number at $t = 0$. This **half-life** is a general property of the decay law.

▶ There exists a certain interval of time, called the half-life, such that after each half-life the number of nuclei that have not yet decayed is reduced by a factor of 2.

Thus, consider a decay in which nuclei X decay into nuclei Y (the daughter nuclei) by, say, alpha emission. Assume that nuclei Y are stable. Then as time goes by, the number of X nuclei is reduced (Figure 2.6a). The number of Y nuclei is increasing with time, as shown in Figure 2.6b.

The half-life can be found from the graph as follows. The initial value is 200×10^{26} nuclei. We find half of this value, i.e. 100×10^{26}, and see that 100×10^{26} corresponds to a time of 5 s. This is the half-life.

We may also define a concept useful in experimental work: that of decay rate or

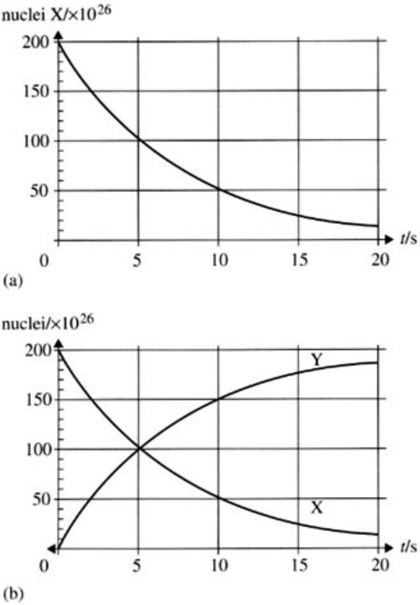

Figure 2.6 (a) The number of nuclei X that have not yet decayed as a function of time. This is an exponential decay curve. (b) The number of the daughter nuclei Y is increasing.

activity A – the number of nuclei decaying per second. It can be shown that activity obeys the same decay law as the number of nuclei, so in a period equal to a half-life the initial activity is reduced by a factor of 2. The unit of activity is the becquerel (Bq): 1 Bq is equal to one decay per second.

Example questions

Q2

An isotope has a half-life of 20 min. If initially there is 1024 g of this isotope, how much time must go by for there to be 128 g left?

Answer

The nuclei have been reduced by a factor of 8. Thus, 3 half-lives or 60 min must have gone by.

Q3

The activity of a sample is initially 80 decays per minute. It becomes 5 decays per minute after 4 h. What is the half-life?

Answer

The activity is reduced from 80 to 5 decays in 4 half-lives. The half-life is 1 h.

Q4

The activity of a sample is 15 decays per minute. The half-life is 30 min. When was the activity 60 decays per minute?

Answer

One half-life before the sample was given to us the activity was 30 decays per minute and one half-life before that it was 60 decays per minute, that is 60 minutes before.

The meaning of a half-life can also be understood in the following sense. Any given nucleus has a 50% chance of decaying within a time interval equal to the half-life. If a half-life goes by and the nucleus has not decayed, the chance of a decay in the next half-life is still 50%. Thus, the probability that a nucleus will have decayed by the second half-life is (see the tree diagram in Figure 2.7) $\frac{1}{2} + \frac{1}{2} \times \frac{1}{2} = \frac{3}{4} = 0.75$ or 75%.

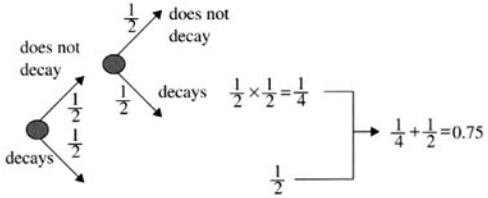

Figure 2.7 Tree diagram for nuclear decay.

(There is more on radioactive decay in Chapter 6.6.)

Questions

1 In a study of the intensity of gamma rays from a radioactive source it is suspected that the counter rate C at a distance d from the source should behave as

$$C \propto \left(\frac{1}{d + d_0}\right)^2$$

where d_0 is an unknown constant. If a set of data for C and d is given, how should these be plotted in order to get a straight line?

2 The intensity of gamma rays of a specific energy (monochromatic rays) falls off exponentially with the thickness x of the absorbing material

$$I = I_0 e^{-\mu x}$$

where I_0 is the intensity at the face of the absorber and μ a constant depending on the material. (See Figure 2.8.)

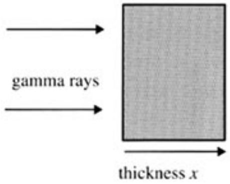

Figure 2.8 For question 2.

How should intensity I and thickness x be plotted in order to allow an accurate determination of the constant μ?

3 A radioactive source has a half-life of 3.00 min. At the start of an experiment there was 32.0 mg of the radioactive material present. How much will there be after 18.0 min?

4 The initial activity of a radioactive sample is 120 Bq. If after 24 h the activity is measured to be 15 Bq, find the half-life of the sample.

5 Beryllium-8 ($^{8}_{4}$Be) decays into two identical particles. What are they?

6 The only stable nuclei with more protons than neutrons are those of hydrogen and helium-3 ($^{3}_{2}$He). Why do you think there are so few?

7 An alpha particle and an electron with the same velocity enter a region of a uniform magnetic field at right angles to the velocity. Explain why they are deflected in opposite directions. Find the ratio of the radii of the circular paths the particles are deflected into.

8 Tritium ($^{3}_{1}$H) is a radioactive isotope of hydrogen and decays by beta decay. Write down the equation for the reaction and name the products of the decay.

9 Nitrogen ($^{14}_{7}$N) is produced in the beta decay of a radioactive isotope. Write down the reaction and name the particles in the reaction.

10 Bismuth ($^{210}_{83}$Bi) decays by beta and gamma emission. Write down the reaction and name the nucleus bismuth decays into.

11 Plutonium ($^{239}_{94}$Pu) decays by alpha decay. Write down the reaction and name the element produced in the decay.

12 A nucleus ($^{A}_{Z}$X) decays by emitting two electrons and one alpha particle. Find the atomic and mass numbers of the produced nucleus.

13 Name the two missing particles in the reaction $^{22}_{11}\text{Na} \rightarrow {}^{22}_{10}\text{Ne} + ? + ?$.

14 Discuss how one could confirm that a particular element emits:
(a) alpha particles;
(b) beta particles;
(c) gamma rays.

15 The track of an alpha particle in a cloud chamber was measured to be 30 mm. The energy required to produce an ion pair is about 32 eV, on average. Assuming that alpha particles create 6000 ions per mm along their path, estimate the energy of the alpha particle.

16 Many of the most stable nuclei have an even number of protons and an even number of neutrons. Can you suggest a reason why this might be so?

17 Explain why the heavy stable nuclei tend to have many more neutrons than protons.

18 Referring to the Segre plot in the text (Figure 2.4), what would be a likely decay for an unstable nucleus that has a large neutron-to-proton ratio? Where on the plot would such a nucleus be? What would be the likely decay for an unstable nucleus that has a small neutron-to-proton ratio? Where on the plot would this nucleus be?