

7 Radioactivity

7.1 INTRODUCTION

If it were not for the fact that a few very long-lived radionuclides occur in nature it is certain that radioactivity would not have been discovered as early as it was. Thorium minerals contain $^{232}_{90}\text{Th}$ and uranium minerals contain $^{235}_{92}\text{U}$ and $^{238}_{92}\text{U}$. The half-lives of these naturally occurring radionuclides are comparable with, or greater than, the age of the earth ($\approx 3 \times 10^9$ y). It must be presumed, therefore, that when earth matter, as we now know it, was created these radionuclides were formed along with the stable nuclides and have been decaying very slowly ever since. The shorter lived radionuclides would have decayed away long ago and are thus not found in nature.

Table 7.1. Uranium and Thorium Minerals

Name	Chemical composition	Colour and form
Autunite	$\text{CaO} \cdot 2\text{UO}_3 \cdot \text{P}_2\text{O}_5 \cdot 8\text{H}_2\text{O}$	Yellow; rhombic
Carnotite	$\text{K}_2\text{O} \cdot 2\text{U}_2\text{O}_3 \cdot \text{V}_2\text{O}_5 \cdot 3\text{H}_2\text{O}$	Yellow; hexagonal, rhombic
Monazite	$(\text{Ce}, \text{Nd}, \text{Pr}, \text{La})\text{PO}_4 + \text{Th}_3(\text{PO}_4)_4$	Yellow, brown; monoclinic
Thorianite	$(\text{Th}, \text{U})\text{O}_2$	Black; cubic
Thorite	ThSiO_4	Black, orange; tetragonal
Torbernite	$\text{Cu}(\text{UO}_2)_2\text{P}_2\text{O}_8 \cdot 12\text{H}_2\text{O}$	Green; tetragonal
Trögerite	$(\text{UO}_2)_3\text{As}_2\text{O}_8 \cdot 12\text{H}_2\text{O}$	Monoclinic
Uraninite	$\text{UO}_3 \cdot \text{UO}_2 + \text{PbO}$	Black, grey; cubic, amorphous
Zeunerite	$\text{Cu}(\text{UO}_2)_2\text{As}_2\text{O}_8 \cdot 8\text{H}_2\text{O}$	Tetragonal

It was in 1896 that the penetrating radiation from thorium and uranium minerals was first noticed. In this year Becquerel observed that potassium uranyl sulphate, $\text{K}_2\text{UO}_2(\text{SO}_4)_2 \cdot 2\text{H}_2\text{O}$, emitted radiations which could penetrate black paper and other substances opaque to visible light, and which had the power to blacken a photographic plate. Later, all other uranium compounds were found to exhibit this property and it became clear that the radiation was to be associated with the uranium content

of the compounds. Following Röntgen's work with X-rays, Becquerel observed that the newly discovered radiation could discharge an electroscope. This was due to the ionization of the air by the radiation. After Becquerel's discovery Pierre and Marie Curie isolated two new elements, radium and polonium, from uraninite. Both elements emitted the penetrating radiation observed by Becquerel and the phenomenon of this emission from certain elements became known as *radioactivity*. Since these early discoveries, many other *radionuclides* have been found, most of which do not occur in nature but which can be made in the laboratory and are called artificial radionuclides.

7.2 GENERAL PROPERTIES OF RADIOACTIVITY

The rate of emission of the primary radiation from any radioactive substance is not influenced by the physical or chemical state of the substance, and it must be concluded that radioactivity is an atomic or nuclear phenomenon. In fact the primary radiations are emitted from the nucleus

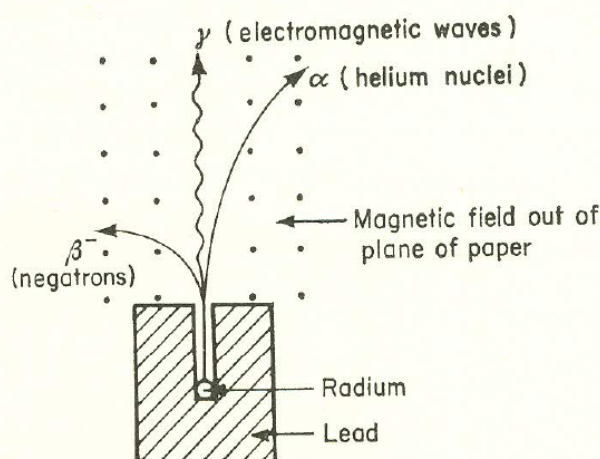


FIG. 7.1. Separation of α -, β - and γ -radiation by the application of a magnetic field

and not from the outer regions of the atom which is relatively empty and contains only the orbital electrons. Certain secondary effects can occur, however, which lead to the emission of extranuclear X-rays and to the ejection of orbital electrons in the so-called electron capture and internal conversion processes to be explained later. Early investigations into the nature of the radiations were made by studying the effects of a magnetic field, the absorptions in different materials, and the ionization produced in gases.

If the radiations from, say, a piece of radium are collimated into a narrow beam and then subjected to a magnetic field as illustrated in Fig. 7.1, it is found that they split into three components. One component, called *alpha* (α)-radiation, is slightly deflected in one direction while another component, called *beta* (β)-radiation, is deflected much more and in the opposite direction. From the deflection directions and the magnetic field direction it is correctly deduced that the α - and β -radiations are streams of high speed positively and negatively charged particles respectively. Further experiments involving the determination of charge to mass ratio for these particles show that the α -particles are helium nuclei and that the β -particles are negatrons. The third component, called *gamma* (γ)-radiation, is undeflected by a magnetic field. The γ -rays were recognized early on as being electromagnetic waves and similar to X-rays but with more energy. The nuclear γ -rays emitted in radioactive processes produce diffraction effects with crystal gratings in the same way that X-rays do, and this can be taken as one proof of their identity.

When the α -, β - and γ -radiations which occur in radioactivity are passed into absorbing materials of different thicknesses, it is the γ -radiation which has the greatest penetrating power while the α -radiation is the most easily absorbed. The relative qualitative absorbing powers of paper, sheet aluminium, and a thick lead slab towards the three radiations are shown in Fig. 7.2.

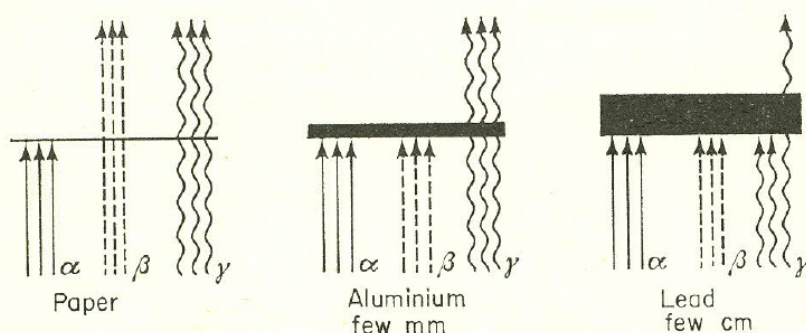


FIG. 7.2. Illustration of the relative penetration powers of the radiations emitted in radioactive processes

The γ -radiation is practically unaffected by the paper and aluminium sheet and is only partly absorbed by the lead. The α -radiation, on the other hand, is completely absorbed by all three absorbers. The β -radiation is hardly affected by the paper but is absorbed by the aluminium and lead. In general, the α - and β -radiations can be easily and completely absorbed by relatively thin layers of any material while the γ -radiation is never quite completely absorbed even by very thick layers of the most dense materials.

When any radioactive radiation, but in particular α - or β -radiation, is passed through a gas, it produces ionization of the gas molecules. If the gas is enclosed between two electrodes maintained at different potentials, an ionization current (I) through the gas results. (See Fig. 7.3.) Although the ionization current is usually small (perhaps 10^{-12} A), it can be measured with an electrometer and forms one basis for the measurement of the intensity of the radiation. The apparatus in which the ionization current is produced is called an ionization chamber. In the early days of

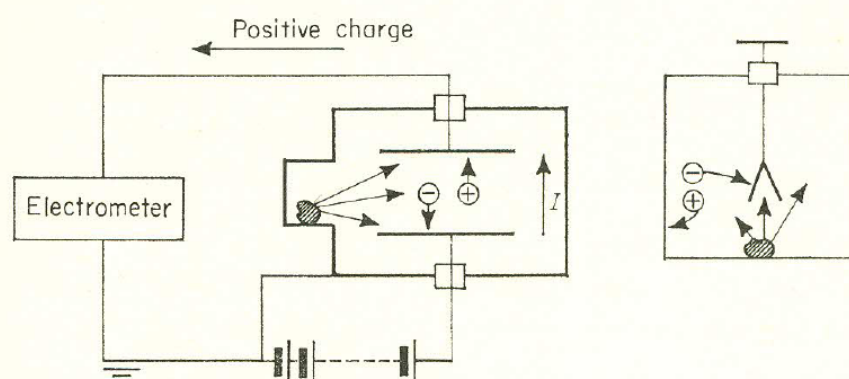


FIG. 7.3. Ionization chamber and electroscope for measuring the intensity of radioactive radiations

radioactivity experiments, an electroscope was used. The ionization produced in the air surrounding the gold leaves of a charged electroscope causes the leaves to lose some of their charge. The deflection of the leaves then indicates the intensity of the radiation passing through the air inside the electroscope. The radioactive substance emitting the radiation is often placed inside the ionization chamber or electroscope, otherwise the α - and β -radiations would be absorbed by the walls of the instrument.

7.3 RADIOACTIVE DECAY LAW

If any radioactive sample is examined for its radioactivity, it is always observed that the strength or activity, as measured by the rate of emission of α -, β and γ -rays, decreases with time. This decay of activity is such that it decreases by the same fraction over equal time intervals. If, for example, the activity decreases from say 100 to 50 per cent over a period of 1 hr, then over the next hour it will decrease from 50 to 25 per cent, over the next hour from 25 to 12.5 per cent, and so on. In other words, the activity goes on decreasing but reaches zero only after an infinitely long time. (See Fig. 7.4.) When the activity of a radioactive sample is plotted against

time, the curve obtained follows the exponential decay law which is applicable to many natural phenomena. The time taken for the activity to decrease to one-half of its initial value is called the *half-life* T , and is a characteristic of each radionuclide. In the above example the half-life is clearly 1 hr. Radionuclides are now known with half-lives ranging from 10^{-6} s to 10^{10} y.

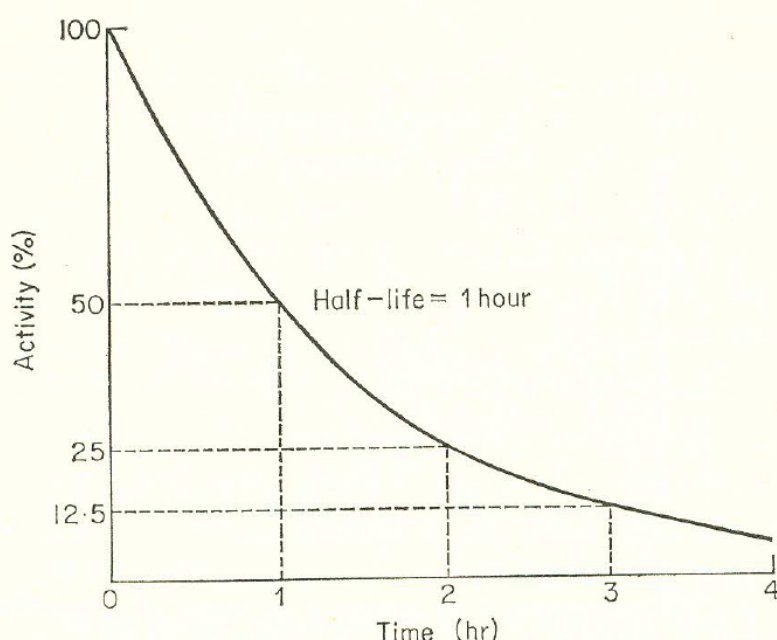


FIG. 7.4. Rate of decay of a radioactive substance having a half-life of one hour

The emission of a γ -ray, α -particle or β -particle is due to a fundamental change in, or disintegration of, the parent atom or nucleus. Any individual atom may decay in this way at any given time but there is no way of predicting just when this will happen. For a very large number of atoms considered together, as is usually the case, the average time which elapses before the atoms decay is significant. This is the reason why each radionuclide has a definite characteristic half-life applicable to a large number of atoms present in any sample of the radionuclide. The *absolute activity* R is defined as the average number of disintegrations occurring per unit time in a given number of radioactive atoms. The *specific activity* is simply the absolute activity per gramme of the pure radionuclide. What is often called the counting rate R' is the number of emitted particles and photons which are detected per unit time, in radioactivity measurements. For a given detecting system R' is nearly always proportional to R for a given radionuclide. This is because for a given geometry the radiation detected will be a constant fraction of the total radiation emitted which in turn is proportional to the disintegration rate. This fact is useful in applying the decay law to half-life determinations.

Consider a radioactive sample containing radioactive atoms of one kind only. If at any time the number of radioactive atoms present is N then it is an experimental fact that the disintegration rate R , or rate of change of N with time, is proportional to N , i.e.

$$R = \frac{dN}{dt} = -\lambda N \quad (7.1)$$

where λ is the constant of proportionality, called the *decay constant*, and the negative sign indicates that the number of atoms, N , is decreasing with time. If N is put equal to unity in equation (7.1), it can be seen that λ is the probability per unit time for the decay of a single atom. Integration of equation (7.1) yields directly the equation

$$N = N_0 \cdot \exp(-\lambda t) \quad (7.2)$$

where N_0 is the number of radioactive atoms at time $t = 0$, and N the number at time t . The half-life T is found in terms of λ by putting $N = \frac{1}{2}N_0$ at time $t = T$ in equation (7.2). Then

$$\frac{1}{2} N_0 = N_0 \cdot \exp(-\lambda T)$$

i.e.

$$T = \frac{0.693}{\lambda}$$

$$\frac{1}{e} = e^{-\lambda T_m} \Rightarrow$$

(7.3)

The *mean-life* T_M is defined as the time which must elapse for an initial number of atoms N_0 to decrease to N_0/e so that

$$T_M = \frac{1}{\lambda} = \frac{T}{0.693} \quad (7.4)$$

Equation (7.2) as it stands is not very useful in the interpretation of experimental observations of radioactive decay since it is the activity or counting rate which is observed rather than N . Differentiating equation (7.2) yields,

$$\frac{dN}{dt} = -\lambda N_0 \cdot \exp(-\lambda t).$$

But $-\lambda N_0$ is the initial activity R_0 at time $t = 0$, so that

$$R = R_0 \cdot \exp(-\lambda t), \quad (7.5)$$

When R is proportional to R' this equation can be re-written in terms of the observed counting rate as

$$R' = R'_0 \exp(-\lambda t). \quad (7.6)$$

On taking logarithms

$$\log_e R' = \log_e R'_0 - \lambda t \quad (7.7)$$

or

$$\log_{10} R' = \log_{10} R'_0 - 0.434 \lambda t. \quad (7.8)$$

For a radioactive sample containing one kind of radionuclide only, a plot of $\log R'$ against t will yield a straight line from which the decay constant and hence the half-life can be calculated according to equations (7.4) and (7.8.) (See Fig. 7.5.) This method of measuring the half-life is clearly limited to life-times of the same order of magnitude as the practicable observation times of the counting rate. For very long half-lives use is made of equation (7.1) by measuring the absolute activity in specially designed counting systems and by measuring the total quantity of the radioactive substance present to give N . In the case of very short lived radionuclides special methods employing coincidence techniques are used, but these are beyond the scope of this book.

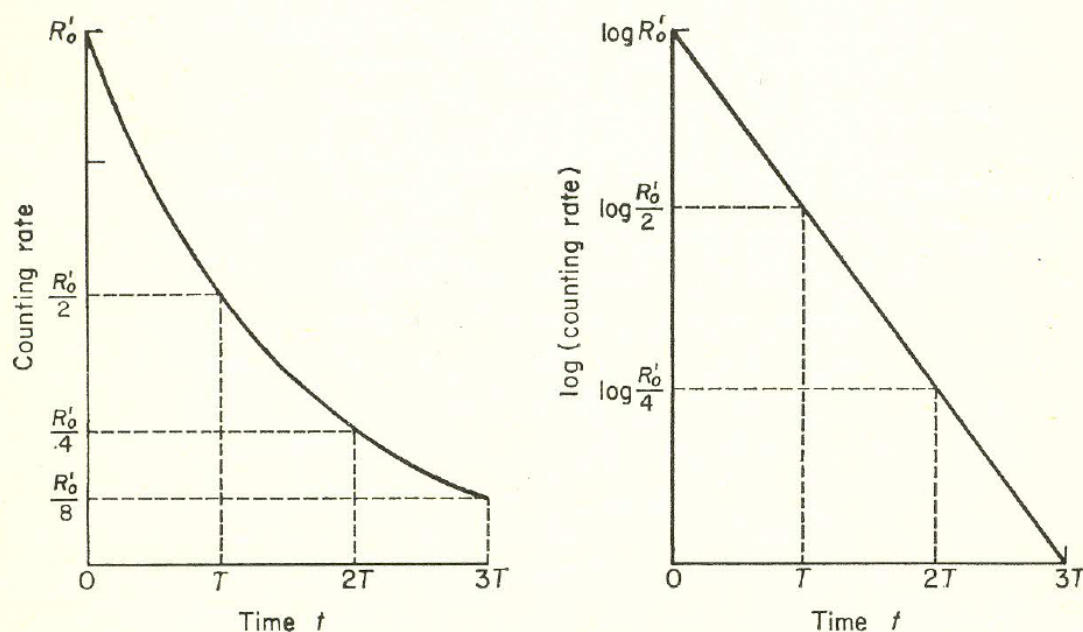


FIG. 7.5. Linear and logarithmic plots of counting rate against time for a single radionuclide

The activities encountered in even the smallest quantities of radioactive substances are so large when expressed in disintegrations per second that it is necessary to make use of one of two units which have been defined for the purpose. The *curie* (c) is equal to the disintegration rate of 1 gramme of radium ($^{226}_{88}\text{Ra}$) or to 3.7×10^{10} disintegrations per sec. The *millicurie* (1 mc = 10^{-3} c) and the *microcurie* (1 μc = 10^{-6} c) are also used. The other unit is the *rutherford* which is defined as 10^6 disintegrations per sec, but this unit has not come into general use. It must be noted here