

CHAPTER 2 RADIOACTIVE DECAY

Introduction

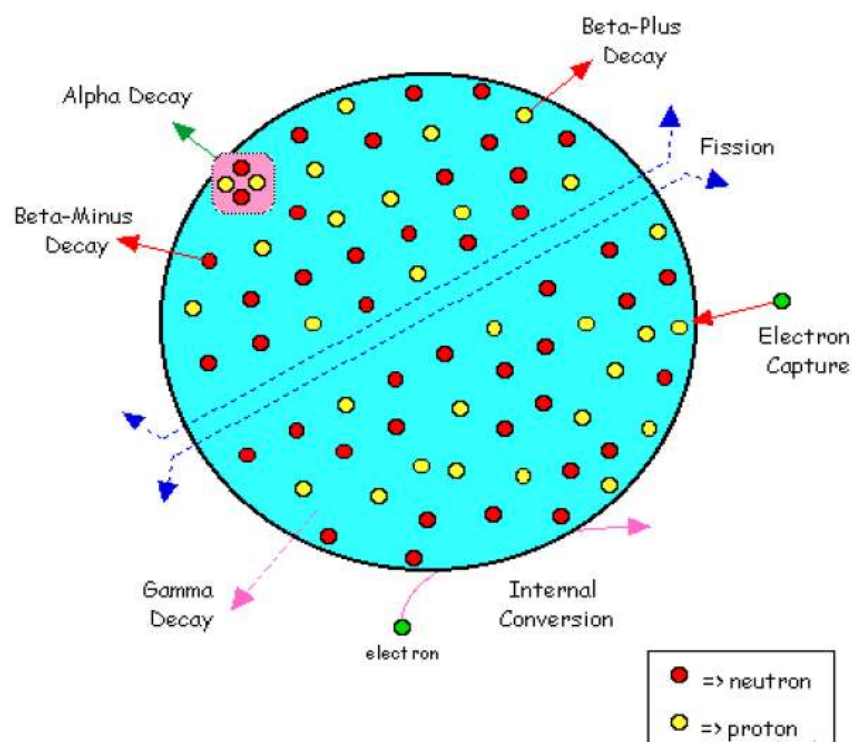
We saw in the last chapter that radioactivity is a process used by unstable nuclei to achieve a more stable situation. It is said that such nuclei decay in an attempt to achieve stability. So, an alternative title for this chapter is Nuclear Decay Processes.

We also saw in the previous chapter that we can use the Nuclear Stability Curve as a means of describing what is going on. So a second alternative title for this chapter is Methods of Getting onto the Nuclear Stability Curve.

We are going to follow a descriptive or phenomenological approach to the topic here by describing in a fairly simple fashion what is known about each of the major decay mechanisms. Once again you may have already covered this material in high school physics. But bear with us because the treatment here will help us set the scene for subsequent chapters.

Methods of Radioactive Decay

Rather than considering what happens to individual nuclei it is perhaps easier to consider a hypothetical nucleus that can undergo many of the major forms of radioactive decay. This hypothetical nucleus is shown below:



Firstly, we can see two protons and two neutrons being emitted together in a process called alpha decay. Secondly, we can see that a proton can release a particle in a process called beta-plus decay, and that a neutron can emit a particle in a process called beta-minus decay. We can also see an electron being captured by a proton. Thirdly we can see some energy being emitted which results from a process called gamma-decay as well as an electron being attracted into the nucleus and being ejected again. Finally, there is the rather catastrophic process where the nucleus cracks in half called spontaneous fission. We will now describe each of these decay processes in turn.

Spontaneous Fission

This is a very destructive process which occurs in some heavy nuclei which split into 2 or 3 fragments plus some neutrons. These fragments form new nuclei which are usually radioactive. Nuclear reactors exploit this phenomenon for the production of radioisotopes. It's also used for nuclear power generation and in nuclear weaponry. The process is not of great interest to us here and we will say no more about it for the time being.

Alpha Decay

In this decay process two protons and two neutrons leave the nucleus together in an assembly known as an **alpha particle**. Note that an alpha particle is really a helium-4 nucleus.

So why not call it a helium nucleus? Why give it another name? The answer to this question lies in the history of the discovery of radioactivity. At the time when these radiations were discovered we didn't know what they really were. We found out that one type of these radiations had a double positive charge and it was not until sometime later that we learnt that they were in fact nuclei of helium-4. In the initial period of their discovery this form of radiation was given the name alpha rays (and the other two were called beta and gamma rays), these terms being the first three letters of the Greek alphabet. We still call this form of radiation by the name alpha particle for historical purposes. Calling it by this name also contributes to the specific jargon of the field and leads outsiders to think that the subject is quite specialised!

But notice that the radiation really consists of a helium-4 nucleus emitted from an unstable larger nucleus. There is nothing strange about helium since it is quite an abundant element on our planet. So why is this radiation dangerous to humans? The answer to this question lies with the energy with which they are emitted and the fact that they are quite massive and have a double positive charge.

So when they interact with living matter they can cause substantial destruction to molecules which they encounter in their attempt to slow down and to attract two electrons to become a neutral helium atom.

An example of this form of decay occurs in the uranium-238 nucleus. The equation which represents what occurs is:



Here the uranium-238 nucleus emits a helium-4 nucleus (the alpha particle) and the parent nucleus becomes thorium-234. Note that the Mass Number of the parent nucleus has been reduced by 4 and the Atomic Number is reduced by 2 which is a characteristic of alpha decay for any nucleus in which it occurs.

Beta Decay

There are three common forms of beta decay:

(a) Electron Emission

Certain nuclei which have an excess of neutrons may attempt to reach stability by converting a neutron into a proton with the emission of an electron. The electron is called a beta-minus particle - the minus indicating that the particle is negatively charged.

We can represent what occurs as follows:



Where a neutron converts into a proton and an electron. Notice that the total electrical charge is the same on both sides of this equation. We say that the electric **charge is conserved**.

We can consider that the electron cannot exist inside the nucleus and therefore is ejected.

Once again there is nothing strange or mysterious about an electron. What is important though from a radiation safety point of view is the energy with which it is emitted and the chemical damage it can cause when it interacts with living matter.

An example of this type of decay occurs in the iodine-131 nucleus which decays into xenon-131 with the emission of an electron, that is



The electron is what is called a beta-minus particle. Note that the Mass Number in the above equation remains the same and that the Atomic Number increases by 1 which is characteristic of this type of decay.

You may be wondering how an electron can be produced inside a nucleus given that the simple atomic description we gave in the previous chapter indicated that the nucleus consists of protons and neutrons only. This is one of the limitations of the simple treatment presented so far and can be explained by considering that the three fundamental particles which we call protons, neutrons and electrons are themselves formed of smaller particles called quarks. We are not going to consider these in any way here other than to note that some combinations of different types of quark produce protons, another combination produces neutrons and a third combination forms electrons. The message here is to appreciate that a simple picture is the best way to start in an introductory text such as this and that the real situation is a lot more complex than what has been described. The same can be said about the treatment of beta-decay given above as we will see in subsequent chapters.

(b) Positron Emission

When the number of protons in a nucleus is too large for the nucleus to be stable it may attempt to reach stability by converting a proton into a neutron with the emission of a positively-charged electron.

That is not a typographical error! An electron with a positive charge also called a positron is emitted. The positron is the beta-plus particle.

The history here is quite interesting. A brilliant Italian physicist, **Enrico Fermi** developed a theory of beta decay and his theory predicted that positively-charged as well as negatively-charged electrons could be emitted by unstable nuclei. These particles could be called pieces of **anti-matter** and they were subsequently discovered by experiment. They do not exist for very long as they quickly combine with a normal electron and the subsequent reaction called annihilation gives rise to the emission of two gamma rays.

Science fiction writers had a great time following the discovery of anti-matter and speculated along with many scientists that parts of our universe may contain negatively-charged protons forming nuclei which are orbited by positively-charged electrons. But this is taking us too far away from the topic at hand!

The reaction in our unstable nucleus which contains one too many protons can be represented as follows:

Notice, once again, that electric charge is conserved on each side of this equation.



An example of this type of decay occurs in sodium-22 which decays into neon-22 with the emission of a positron:



Note that the Mass Number remains the same and that the Atomic Number decreases by 1.

(c) Electron Capture

In this third form of beta decay an inner orbiting electron is attracted into an unstable nucleus where it combines with a proton to form a neutron. The reaction can be represented as:

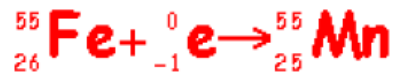


This process is also known as K-capture since the electron is often attracted from the K-shell of the atom.

How do we know that a process like this occurs given that no radiation is emitted? In other words the event occurs within the atom itself and no information about it leaves the atom. Or does it? The signature of this type of decay can be obtained from effects in the electron cloud surrounding the nucleus when the vacant site left in the K-shell is filled by an electron from an outer shell. The filling of the vacancy is associated with the emission of an X-ray from the electron cloud and it is this X-ray which provides a signature for this type of beta decay.

This form of decay can also be recognised by the emission of gamma-rays from the new nucleus.

An example of this type of radioactive decay occurs in iron-55 which decays into manganese-55 following the capture of an electron. The reaction can be represented as follows:

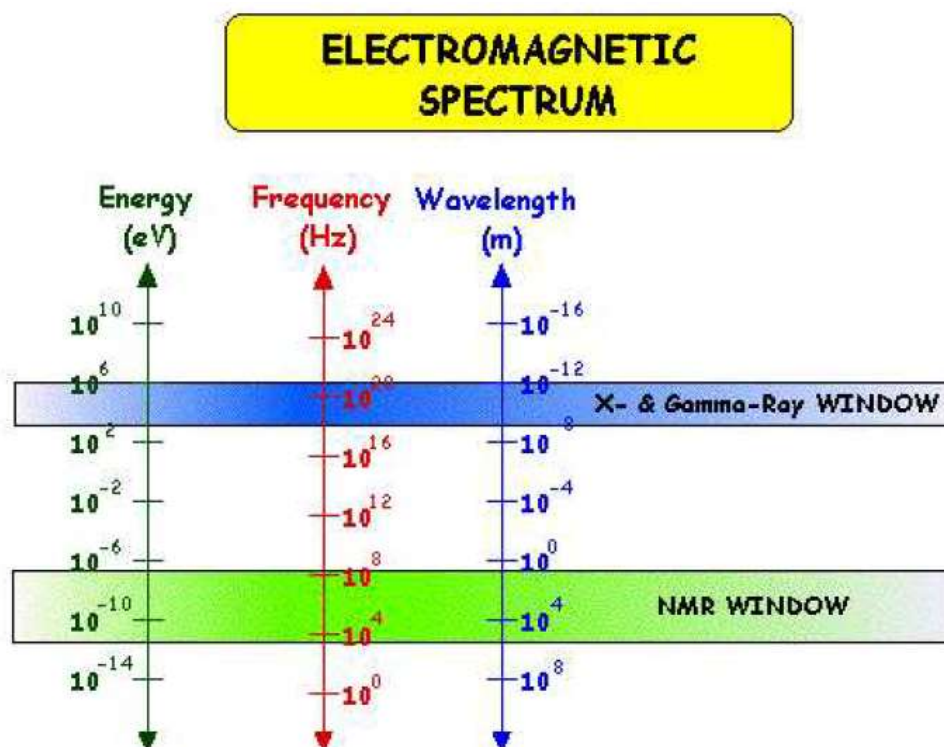


Note that the Mass Number once again is unchanged in this form of decay and that the Atomic Number is decreased by 1.

Gamma Decay

Gamma decay involves the emission of energy from an unstable nucleus in the form of electromagnetic radiation.

You should remember from your high school physics that **electromagnetic radiation** is the biggest physical phenomenon we have so far discovered. The radiation can be characterised in terms of its frequency, its wavelength and its energy. Thinking about it in terms of the energy of the radiation we have very low energy electromagnetic radiation called radio waves, infra-red radiation at a slightly higher energy, visible light at a higher energy still, then ultra-violet radiation and the higher energy forms of this radiation are called X-rays and gamma-rays. You should also remember that these radiations form what is called the Electromagnetic Spectrum.



Before proceeding it is useful to pause for a moment to consider the difference between X-rays and gamma-rays. These two forms of radiation are high energy electromagnetic rays and are therefore virtually the same. The difference between them is not what they consist of but where they come from. In general we can say that if the radiation emerges from a nucleus it is called a gamma-ray and if it emerges from outside the nucleus from the electron cloud for example, it is called an X-ray.

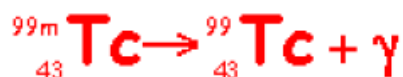
One final point is of relevance before we consider the different forms of gamma-decay and that is what such a high energy ray really is. It has been found in experiments that gamma-rays (and X-rays for that matter!) sometimes manifest themselves as waves and other times as particles. This **wave-particle duality** can be explained using the equivalence of mass and energy at the atomic level. When we describe a gamma ray as a wave it has been found useful to use terms such as frequency and wavelength just like any other wave. In addition when we describe a gamma ray as a particle we use terms such as mass and electric charge. Furthermore the term **electromagnetic photon** is used for these particles. The interesting feature about these photons however is that they have neither mass nor charge!

There are two common forms of gamma decay:

(a) Isomeric Transition

A nucleus in an excited state may reach its ground or unexcited state by the emission of a gamma-ray.

An example of this type of decay is that of **technetium-99m** - which by the way is the most common radioisotope used for diagnostic purposes today in medicine. The reaction can be expressed as:



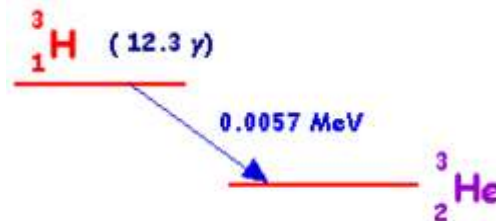
Here a nucleus of technetium-99 is in an excited state, that is it has excess energy. The excited state in this case is called a metastable state and the nucleus is therefore called technetium-99m (m for metastable). The excited nucleus loses its excess energy by emitting a gamma-ray to become technetium-99.

(b) Internal Conversion

Here the excess energy of an excited nucleus is given to an atomic electron, e.g. a K-shell electron.

Decay Schemes

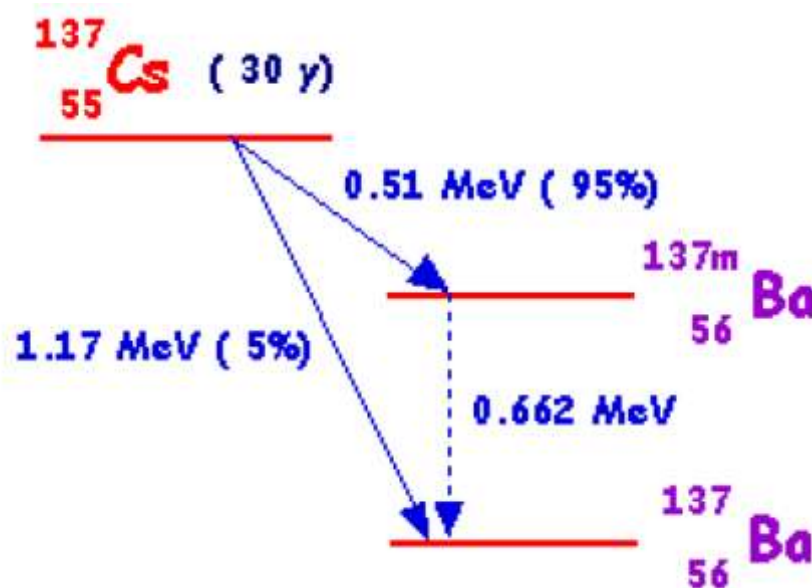
Decay schemes are widely used to give a visual representation of radioactive decay. A scheme for a relatively straight-forward decay is shown below:



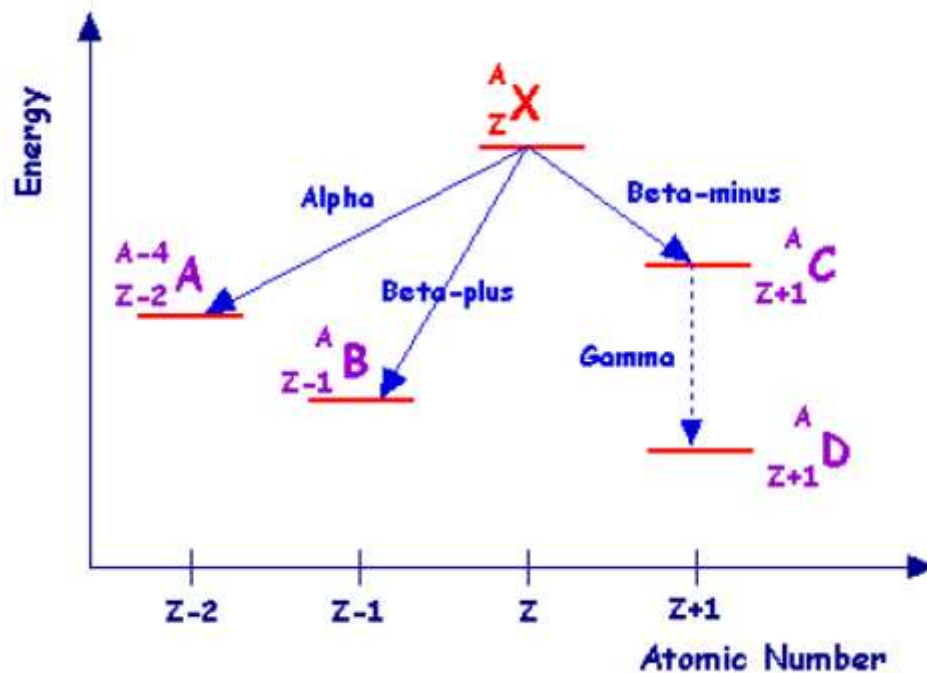
This scheme is for hydrogen-3 which decays to helium-3 with a half-life of 12.3 years through the emission of a beta-minus particle with an energy of 0.0057 MeV.

A scheme for a more complicated decay is that of caesium-137:

This isotope can decay through two beta-minus processes. In one which occurs in 5% of disintegrations a beta-minus particle is emitted with an energy of 1.17 MeV to produce barium-137. In the second which occurs more frequently (in the remaining 95% of disintegrations) a beta-minus particle of energy 0.51 MeV is emitted to produce barium-137m - in other words a barium-137 nucleus in a metastable state. The barium-137m then decays via isomeric transition with the emission of a gamma-ray of energy 0.662 MeV.



The general method used for decay schemes is illustrated in the diagram below:



The energy is plotted on the vertical axis and atomic number on the horizontal axis - although these axes are rarely displayed in actual schemes. The isotope from which the scheme originates is displayed at the top - X in the case above. This isotope is referred to as the parent. The parent loses energy when it decays and hence the products of the decay referred to as daughters are plotted at a lower energy level.

The diagram illustrates the situation for common forms of radioactive decay. Alpha-decay is illustrated on the left where the mass number is reduced by 4 and the atomic number is reduced by 2 to produce daughter A. To its right the scheme for beta-plus decay is shown to produce daughter B. The situation for beta-minus decay followed by gamma-decay is shown on the right side of the diagram where daughters C and D respectively are produced.