An Introduction to Radioactivity

by

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This text is intended as an introduction to the process of radioactivity for those who encounter radioactive materials in their work and who would like to better understand the phenomenon, but whose education did not include physics to the appropriate level. I have tried to explain the relevant science in a manner which should be understandable by those without a formal physics background and to that end the mathematics has been kept to an absolute minimum. I have however deliberately not compromised on the factual detail, believing that it is easier to understand the subject if it is explained fully rather than using a watered down version which glosses over some half truths in order to avoid supposedly difficult areas. I have also tried to include relevant historical detail in order to add some human interest to the facts. Whilst writing I have had in mind a readership mainly of those who use radioactivity in medical applications, such as radioimmunoassay, haematology, nuclear medicine and therapeutic applications, and so I have drawn examples from these fields. However the text would also be equally relevant to non-medical users of radioactivity.

1 Introduction

Radioactivity is a phenomenon that occurs naturally in a number of substances. Atoms of the substance spontaneously emit invisible but energetic radiations, which can penetrate materials that are opaque to visible light. The effects of these radiations can be harmful to living cells but, when used in the right way, they have a wide range of beneficial applications, particularly in medicine. Radioactivity has been present in natural materials on the earth since its formation (for example in potassium-40 which forms part of all our bodies). However, because its radiations cannot be detected by any of the body's five senses, the phenomenon was only discovered 100 years ago when radiation detectors were developed. Nowadays we have also found ways of creating new man made sources of radioactivity; some (like iodine-131 and molybdenum-99) are incidental waste products of the nuclear power industry which nevertheless have important medical applications, whilst others (for example fluorine-18) are specifically produced for the benefits of their medical use.

2 The discovery of radioactivity

Radioactivity was discovered in 1896 by the French physicist, Henri Becquerel working in Paris. The story of the discovery is a fascinating one which is worth telling in some detail. It gives interesting insights into how quickly and easily fundamental experiments could be done 100 years ago, compared with the lengthy processes of modern scientific research.

Becquerel had succeeded his father as Professor of Physics at the Museum of Natural History in Paris. There he continued his father's investigations into the phenomenon of phosphorescence; the emission of visible light by certain substances when they are activated by exposure to a bright light source. He had assisted his father with many experiments on phosphorescence and knew that a preparation containing crystals of uranium and potassium would glow when exposed to sunlight and that this stopped quickly when it was taken into the dark.

On 20 January 1896 Becquerel attended a lecture at the French Academy of Science in Paris at which he heard Henri Poincaré describe the recent discovery of X-rays by Wilhelm Röntgen. Poincaré demonstrated how, when a beam of electrons was accelerated across a vacuum tube, visible light was emitted from the spot where the electron beam hit the glass wall (just like in a modern TV tube). This was another example of phosphorescence (although nowadays we would call it fluorescence) which others had observed before. The new discovery which Röntgen had made in 1895 was that some hitherto unknown invisible radiation was also emitted from the same spot. These became known as X-rays (X standing for the unknown). Röntgen had found that they were able to penetrate solid material and cast shadows of metal objects on photographic paper. Hearing this description, Becquerel presumed that the X-rays were associated with the phosphorescence and he wondered whether his phosphorescent crystals might also emit X-rays. He therefore conducted several experiments to check this. In each experiment he wrapped a photographic plate in light tight paper and placed some of his crystals on the outside of the paper. This was then exposed to sunlight for several hours. Sure enough, when the plate was developed it had become blackened where the crystals had been. He found that if a thin piece of metal was placed between the crystals and the plate then this cast a shadow. These results seemed to confirm his assumption that X-rays were part of phosphorescence and he reported these results to the French Academy of Science on 24 February 1896.

Continuing his experiments, Becquerel prepared some more samples on 26 and 27 February but the weather was poor and there was insufficient sunlight to activate his crystals, so did not use them. Instead he left the crystals lying on the wrapped photographic plate but in a dark drawer. By Sunday 1 March the sun still had not shone in Paris, but Becquerel decided to develop his plates anyway, expecting to find only very weak images. Instead he was amazed to find an image just as intense as when the crystals has been exposed to bright sunlight. He immediately did further experiments which confirmed that the crystals could blacken a photographic plate whether or not they were made to phosphoresce. He realised that he had accidentally discovered an entirely new phenomenon which he attributed to some form of long lasting phosphorescence emitting invisible radiation. He presented

his findings to a meeting of the French Academy of Sciences the very next day on 2 March 1896 and a written version of this was published within 10 days. By the end of the year he had published six more papers on his further investigations into these 'Becquerel rays' confirming that they derived from the uranium in his crystals and that they did not noticeably diminish in intensity even after several months.

It is interesting to speculate what might have happened if Becquerel had chosen a different phosphorescent crystal for his experiments. He could just as easily have chosen zinc sulphate from his father's large collection of phosphorescent materials, and then he would not have found any effect on the photographic plate because zinc is not radioactive like uranium. In that case the discovery of radioactivity might well have been left to an Englishman. On 23 February 1896 Silvanus Thompson, in London, had independently performed the same experiment as Becquerel, exposing uranium crystals to sunlight whilst placed on a wrapped photographic plate. By the time that Thompson wrote to the president of the Royal Society in London to describe his results, Becquerel's initial findings had already been reported to the French Academy of Sciences. Hearing this, Thompson did no further work on the subject and thus missed the opportunity to beat Becquerel to his fortuitous discovery of 1 March. That is why we now measure radioactivity in units of megabecquerels rather than megathompsons.

By the end of 1896 Becquerel's interest in his new discovery seems to have waned as he could see little more of interest to do and Röntgen's X-rays seemed to have many more applications. However in 1897 he was joined by a young research student, Marie Curie, who wished to study for her doctorate. Marie soon discovered that another element, thorium, also exhibited the same emission of Becquerel rays as uranium and she suggested the term 'radioactivity' for the phenomenon. She also discovered the important fact that the radioactivity was a property of the atoms themselves and it was not changed by any physical or chemical processes through which the material went. She was later joined by her husband, Pierre, and together they discovered that the mineral pitchblende contained two even stronger radioactive substances, which they called polonium and radium. After years of painstaking purification they were able to separate sufficient polonium and radium to demonstrate that these were both previously unknown elements. In 1903 Henri Becquerel, Marie Curie and Pierre Curie were jointly awarded the Nobel prize in physics for their work on radioactivity. Later Marie Curie was also awarded the 1911 Nobel prize in Chemistry for her discovery of radium.

Radioactivity had also captured the interest of another student, Ernest Rutherford, who was then studying in Cambridge under professor J J Thomson. He continued this interest after he moved to McGill University in Montreal, where he discovered that the Becquerel rays contained two different components which he simply called alpha and beta. The alpha rays were easily stopped by thin card whereas the beta rays would pass through card but were stopped by sheets of metal. Becquerel and the Curies showed that the beta rays were identical to electrons (newly discovered by J J Thomson). Subsequently a third, even more penetrating, component of the radiation was discovered by Paul Villard in Paris and these were naturally called gamma rays. Further investigations by Rutherford, working with the chemist Frederick Soddy, showed that the intensity of radioactive emission of many materials reduced exponentially with time, but that they sometimes converted into other materials which were themselves radioactive. By 1902 Rutherford had concluded that the atom, previously thought to be indestructible, was spontaneously disintegrating and changing from one element into another. This heretical idea was not readily accepted by many scientists who though that it sounded too much like alchemy. However, by 1907 Rutherford and Soddy had identified several separate series of naturally occurring radioactive transformations in which each element successively changed into the next one down the chain, until they eventually ended up as non-active lead.

In 1907 Rutherford moved to Manchester where he was appointed professor of physics, and in 1908 he proved that alpha rays were in fact ionised helium atoms. In 1911 two of his researchers, Hans Geiger and Ernest Marsden, performed a classic experiment in which they allowed alpha particles to scatter off a gold foil and found that some of them bounced straight back. The results of this experiment led Rutherford to deduce that there was a small nucleus at the centre of each atom. Our modern understanding of the nature of the atom and the process of radioactive decay stem largely from the theories developed by Ernest Rutherford and Niels Bohr during this period in Manchester.

3 Fundamental Particles

Nowadays scientists know of a large number of so called fundamental particles which form the building blocks of matter. Fortunately it is only necessary to be aware of a few of these in order to understand the processes involved in radioactivity.

The *electron* is probably the most familiar of these particles and, although we do not see individual electrons, we are well aware of their effects in everyday life. It is the flow of many electrons down wires which constitutes the current that powers so many electrical devices on which the modern world relies. It is the movement of smaller numbers of electrons inside semiconductor materials which forms the basis of all electronic 'microchip' devices. It is also a beam of electrons from a heated filament inside a television tube which causes the phosphors on the front of the tube to glow and form the picture.

The electron was first discovered in an apparatus very similar to a TV tube called a 'Crookes tube'. In 1897 Sir Joseph (J J) Thomson found that the cathode rays emitted from the negative electrode of a Crookes tube were in fact particles. He identified that these were negatively charged and extremely light. Although we can now measure the mass of an electron accurately (9×10^{-28} g) we cannot determine its size. It is so small that even to the best of modern experimental measurements it cannot be distinguished from a perfect point.

The next fundamental particle to be discovered was the *proton*. The first evidence for this came in 1898 when Wilhelm Wien investigated the rays emanating from a hole in the negative electrode of a Crookes tube. In 1911 J J Thomson found that the lightest of these positive rays was about 2000 times heavier than an electron and carried a positive charge. The particles were given the name proton in 1920 by Ernest Rutherford when he realised that they were a fundamental constituent of all atoms. Although the proton is much heavier than the electron, it is still inconceivably light (1.7×10^{-24} g) so that even a million, million protons would still only weight one millionth of a microgram. A proton is also incredibly small but, unlike an electron, its size is measurable with modern experiments. The positive charge on a proton is exactly equal and opposite to the negative charge on an electron.

The other fundamental constituent of an atom is the *neutron*. By 1920 Rutherford had realised that the atom must also contain other particles similar to the proton but without any charge, but it was not until 1932 that James Chadwick discovered the neutron. The neutron has a size and mass nearly the same as the proton but has no electrical charge.

In 1926 the theoretical physicist Paul Dirac had predicted the existence of particles like the electron but with a positive charge. These *positrons* were first detected in 1932 by Carl Anderson studying tracks of cosmic rays. Positrons have the same mass as electrons but a positive charge instead of a negative one. They are in fact antiparticles of the electron and will annihilate with an electron if allowed to come to rest near one.

The only other fundamental particle which we need to mention is the *neutrino*. This was proposed by Wolfgang Pauli in 1930 as a theoretical possibility to explain some of the observations of radioactive decay. The name neutrino was given to the particle by Enrico Fermi in 1934. However it was not experimentally verified until 1956 when nuclear reactors became available. The neutrino carries no charge and practically no mass and so it is hardly surprising that it is extremely difficult to detect.

4 Units

The scale of everything involved with the atom is so far removed from everyday life that it is common to use special units of measurement which are more appropriate to the subject.

The standard scientific unit of energy is the Joule. This is already a rather small unit, being equal to the amount of energy given out by a 1 watt torch bulb in 1 second. However the energies involved in radioactive decay are very much less still, and so the energy of atoms is usually measured in units of *electron volts*. One electron volt (written eV) is the energy gained by an electron when it moves through a voltage of one volt. In atoms we commonly encounter energies of one thousand electron volts (written 1 keV) or one million electron volts (written 1 MeV). These are still very small amounts of energy. It would need 6 million, million MeV to power our torch bulb for 1 second. We only get large amounts of energy from nuclear power, for example, because there are an extremely large number of atoms in each gram of fuel.

The natural unit to use for electric charge is the charge of the proton. In these units the electron has a charge of -1 and the proton and positron a charge of +1. Likewise the proton forms a natural unit of mass in which the proton and neutron each have a mass of 1 unit and the electron and positron each have a mass of only 0.0005 units. Through Albert Einstein's famous relationship $E = mc^2$ it is possible to relate units of mass and energy. In energy units the mass of an electron is equivalent to 511 keV and the mass of a proton to 938 MeV.

The amount of radioactivity in a source is measured by the rate at which atoms undergo radioactive disintegration. The natural unit for this is disintegrations per second (dps) and, in honour of the discoverer of radioactivity, this has been given the special unit name of the becquerel. One becquerel (written 1 Bq) is equal to 1 disintegration per second (1 dps) but we commonly encounter much larger quantities so we use the following:

1 dps		= one becquerel,	written as 1 Bq
1 thousand dps	= 10^3 becquerels	= one kilobecquerel,	written as 1 kBq
1 million dps	= 10^6 becquerels	= one megabecquerel,	written as 1 MBq
1 billion dps	= 10^9 becquerels	= one gigabecquerel,	written as 1 Gbq

An older unit of activity, which is still found in some textbooks (and is still used in America), is the curie. One curie (written 1 Ci) is the activity of one gram of radium and is rather large, being equal to 37 GBq. Therefore we may encounter the following smaller units:

	one curie,	written 1 Ci	= 37 Gbq
one thousandth of a curie	= one millicurie,	written 1 mCi	= 37 MBq
one millionth of a curie	= one microcurie,	written 1 Ci	= 37 kBq.

5 Half-life

Early investigations by Becquerel and the Curies and also by Rutherford and Soddy had shown that the activity of a radioactive source reduced over a period of time which was different for each substance. The time taken for the activity to fall to half of its original value is called the *half-life* of the source. However the activity does not fall at a steady rate, so it is <u>not</u> the case that the activity will have fallen to nothing after two half-lives. Instead the activity falls at an ever decreasing rate so that in every half-life the activity will halve.

Figure 1 shows a graph of how the activity of a source changes with time. If the activity starts out at a value A_0 then after one half-life the activity will have fallen to half of A_0. After two half-lives the activity will have fallen to one quarter of A_0 and after three half-lives to one eighth of A_0. It can be seen that the activity is falling more and more slowly and, in principle, it will never actually reach zero. In

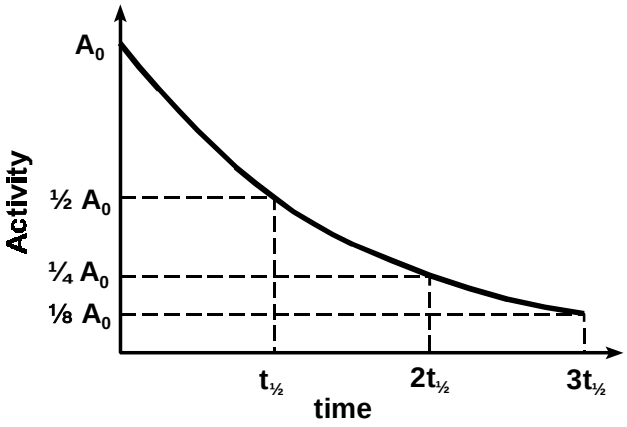


Figure 1 - Exponential decay of activity

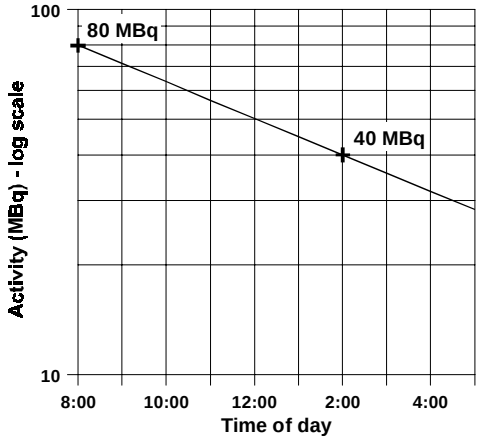


Figure 2 - Exponential decay on a logarithmic scale

practice after a sufficiently long time the activity will have fallen to a negligible level. The shape of a curve like this is said to be *exponential* and so radioactivity is said to exhibit *exponential decay*. Mathematically it can be described by the formula

$$A_t = A_0 e^{-0.693 \frac{t}{t_{½}}}$$

where $t_{½}$ is the half-life. A_t represents the activity at time t and A_0 is the activity at time zero. The symbol 'e' represents a number which is the base of natural logarithms and the function e^x is programmed into most scientific calculators. A special property of the exponential curve is that, although it is not a straight line when plotted normally as in figure 1, if plotted on a logarithmic vertical axis, as in figure 2, it will appear as a straight line. This makes it easy to read off the activity at any time.

Figure 2 shows an example for the decay of a source with a half-life of 6 hours. The vertical axis, plotted on a logarithmic scale using special log-linear graph paper, shows an initial activity of 80 MBq at 8:00 am. After one half life (2:00 pm) this must have fallen by one half to 40 MBq so these two points can be plotted and joined by a straight line (on the logarithmic graph scale). The activity at any time can then simply be read off the graph; for example at midday the activity of the source would be 50 MBq.

The same result can be obtained without drawing the graph by using a calculator and the exponential equation above. The first thing that we need to work out is the exponent of the exponential (the superscript following e) which is $-0.693\ t / t_{½}$. We first calculate *t* divided by $t_{½}$ which represents time since the activity was measured (4 hours in this case) divided by the half-life (6 hours in this case); so on the calculator we enter 4, divide by 6. Then we multiply the result by 0.693 and make the answer negative using the +/- button on the calculator. The result should give -0.46 which is the exponent that we need. Then use the calculator's e^x function (which should give 0.63) and multiply the result by A_0 (80 in this case) to give the answer 50.4.

6 The atom

We now know that all matter is made up of *atoms,* which are often bound together into groups to form *molecules*. Each atom consists of a *nucleus* at its centre surrounded by a cloud of orbiting electrons as illustrated in figure 3. In reality of course an atom is extremely small, only a fraction of a nanometre in diameter, so that it can hardly be seen even by the most powerful of modern microscopes and this structure has been deduced by experiment rather than by direct observation. The nucleus at the centre of the atom is in fact ten thousand times smaller than the complete atom and if figure 3 was drawn to scale the nucleus would not be visible at all. If an atom were magnified one thousand million times it would be about the size of a small party balloon, and on this scale the nucleus would still only be the size of a speck of dust. Most of the atom is empty apart from the very diffuse cloud of orbiting electrons and the minute speck of nucleus at its centre.

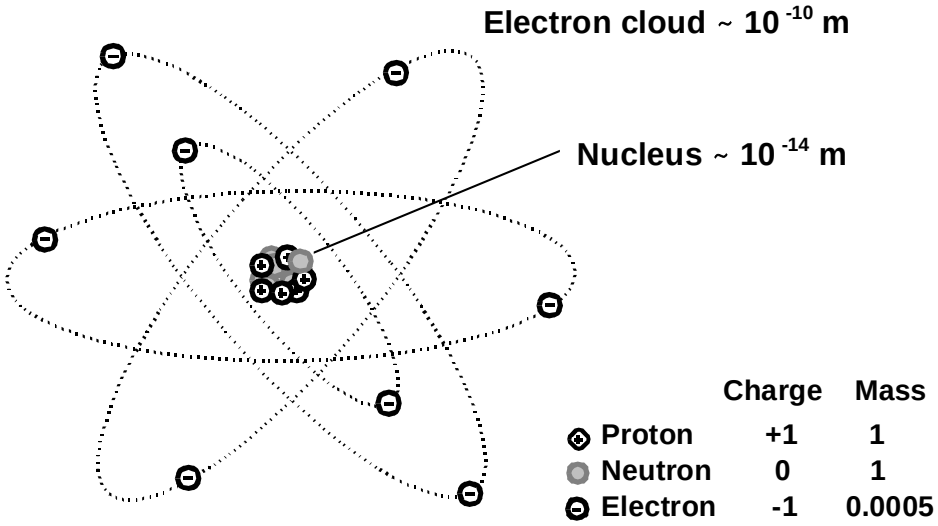


Figure 3 - An atom

The nucleus of an atom is composed of protons and neutrons. The number of protons in the nucleus is called the *atomic number*, and is given the symbol Z. Because the protons each have a charge of +1 unit and the neutrons have no charge, the total charge of the nucleus is +Z units. Electrostatic attraction between the positively charged nucleus and the negatively charged electrons holds exactly Z electrons in orbit around the nucleus when the atom is in its normal state. The overall charge on the atom is then zero. Since atoms combine with one another to form molecules through the interaction of their electrons, it is the arrangement of the atomic electrons which determines the chemistry of the atom. All atoms with the same Z therefore belong to the same *element*, because they behave the same chemically.

The protons and neutrons in the nucleus are collectively called *nucleons*. Despite its small size the nucleus contains nearly all the mass of the atom because each nucleon is 2000 times heavier than an electron. Therefore the total mass of the atom is given by the sum of the number of protons, Z, and the number of neutrons, N, that it contains. Thus the *mass number*, A, of the atom is given by A = Z + N.

The term *nuclide* is used to describe a particular nuclear species with a given combination of A and Z. The full description of a nuclide is given by writing the chemical symbol for its element with A as a superscript and Z as a subscript. Thus the normal form of iodine would be written

$$^{127}_{53}\mathrm{I}$$

where 127 is the mass number, A, and 53 is the atomic number, Z. This nuclide therefore has 53 protons and 74 neutrons (to make a total of 127 nucleons) in its nucleus and 53 orbiting electrons. However iodine always has Z = 53 so, if the chemical symbol is given, the subscript is superfluous and it is often omitted giving ^{127}I. In ordinary text this can also be written as iodine-127.

For an element with atomic number, Z, it is possible to have several different mass numbers, A, by having different numbers of neutrons. These are called *isotopes* of the element. The isotopes all behave the same chemically (because they have the same Z) but have different masses. Thus ^{124}I, ^{125}I, ^{127}I and ^{131}I are all isotopes of iodine with mass numbers 124, 125, 127 and 131 respectively. They all have 53 protons and 53 electrons but they have respectively 71, 72, 74 and 78 neutrons in their nucleus.

6.1 Atomic energy levels

As Rutherford and Bohr discovered, the electrons in an atom can only exist in well defined orbits, or shells, each with a specific energy level. Each shell can only hold a certain number of electrons so, as more electrons are added, they must exist in higher energy levels as the lower shells become full. Since it is the outer electrons which interact chemically with other atoms, this explains why the table of the elements exhibits a periodicity, with similar chemical properties repeated as each energy shell becomes full.

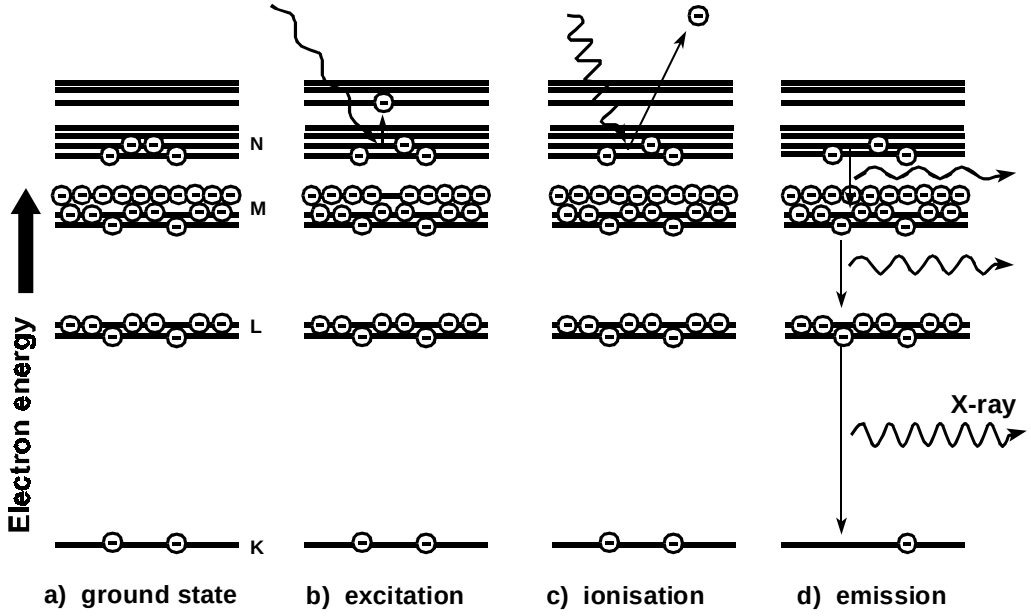


Figure 4 - Atomic energy levels

Figure 4 illustrates some atomic energy levels with the so called K, L, M and N shells at successively higher energies. The K shell can hold a maximum of 2 electrons and the L shell a maximum of 8. The outer, partly filled, shell contains the *valency electrons* which define the chemistry of the atom. Figure 4a shows the *ground state* of the atom in which the electrons fill the lowest possible levels. Figure 4b shows that *excitation* occurs when one of the electrons is raised to a higher energy level by absorption of some incoming energy. *Ionisation* occurs when the absorbed energy is sufficient to eject an electron from the atom altogether (figure 4c). In this case the atom will be left with an overall positive charge. Figure 4d shows what happens if an electron from an inner shell is removed. The vacancy remaining immediately becomes filled by other electrons from the higher shells cascading down to fill the gap. In doing so they loose energy corresponding to the energy difference between the shells, which usually corresponds to a few keV. This energy is released by the emission of one or more *characteristic X-rays*, so called because their energies are characteristic of the element involved.

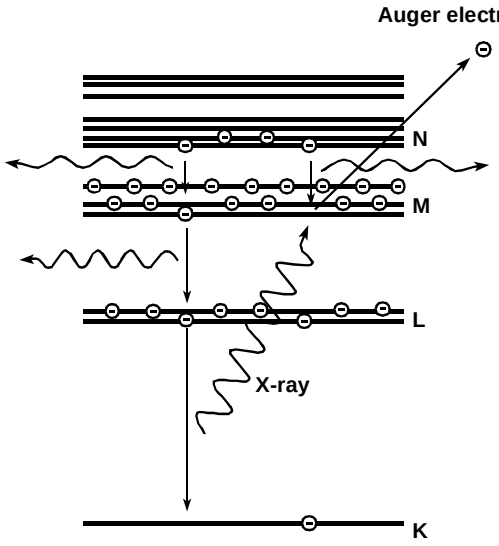


Figure 5 - Auger emission

Sometimes the atom fails to emit the expected X-rays and instead gets rid of its energy by ejecting another electron from the atom. Figure 5 illustrates this process which is called *auger emission* and results in the production of low energy electrons called *auger electrons*.

6.2 Nuclear energy levels

In the same way that atomic electrons can only exist in well defined energy shells, the nucleons in an atomic nucleus also exist in specific energy levels. The situation in the nucleus is however complicated by the fact that there are two types of nucleon, protons and neutrons, to accommodate. Whereas the electrons are held in their shells by electrostatic attraction to the nucleus, the nucleons are held together by the much stronger nuclear force. This is a short range attractive force which exists between protons and neutrons and is strong enough to overcome the electrostatic repulsion which exists between the charged protons.

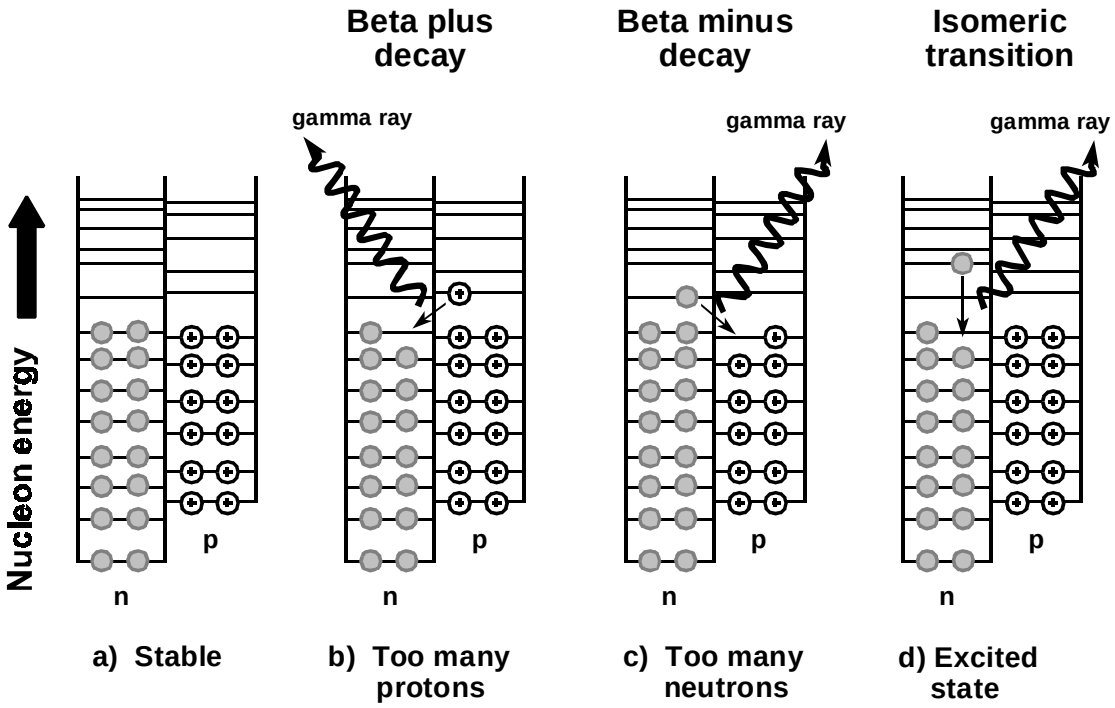


Figure 6 - Nuclear energy levels

Figure 6 illustrates some schematic nuclear energy levels, with two sets of levels, one for protons and one for neutrons. Because the charged protons experience an electrostatic repulsion between them which the uncharged neutrons do not, the proton levels appear at slightly higher energies than the neutron levels. The energy levels involved are of the order of MeV, much higher than the energies of atomic electron levels. As in the case of atomic electrons each nuclear level can only hold a certain number of protons or neutrons, in this case only 2 protons or two neutrons in each level. Figure 6a shows a nucleus with its lowest energy levels all occupied. This nucleus is stable and therefore non-radioactive. Note that, because of the higher energy of the proton levels, stable nuclei will tend to have slightly more neutrons than protons. Figure 6b illustrates a nucleus with too many protons to be stable. It has a single proton in a high energy level with a vacancy for a neutron in a lower level. If it can turn a proton into a neutron it could decay to a lower energy configuration as shown and in doing so emit its excess energy as a gamma ray. This process is called beta plus decay. Figure 6c shows the opposite situation which occurs if a nucleus has too many neutrons for stability. In this case the nucleus can decay to a lower energy if it converts a neutron into a proton, a process called beta minus decay. Figure 6d illustrates a different case where the nucleon configuration is in an excited state from where it can decay by isomeric transition without needing to change the numbers of protons or neutrons.

Internal conversion is a process that may follow gamma emission and is analogous to auger emission in the case of X-rays. In internal conversion a gamma ray which that has been emitted from a decaying nucleus gives up its energy to eject an atomic electron. Thus instead of a gamma ray an *internal conversion electron* is emitted. Since this will leave a vacancy in one of the electron shells it will inevitably be followed by the emission of characteristic X-rays.

It is worth noting that both X-rays and gamma rays are just high energy electromagnetic radiation. The only difference between X-rays and gamma rays is their origin. Characteristic X-rays originate from electron transitions between atomic energy levels, whereas gamma rays originate from nucleon transitions between energy levels in the nucleus. Gamma rays tend to have higher energy than X-rays but this is not always the case. X-rays can also be produced when electrons are stopped violently, as in an X-ray tube, but this produces a spread of energies rather than a single energy.

7 Radioactive Processes

Figure 7 shows a simplified *chart of the nuclides* which is formed by plotting the number of neutrons, N, on the horizontal axis and the number of protons, Z, on the vertical axis. Each square therefore represents a different nuclide. The black squares show all the non-radioactive nuclides which lie along a diagonal line of stability. Near the bottom of the chart these stable nuclei tend to have approximately equal numbers of protons and neutrons, but further up the chart stable nuclei require increasingly more neutrons than protons. Careful inspection also shows that nuclei with even numbers of protons and neutrons are more likely to be stable than odd numbers. This behaviour is exactly what is expected from the nuclear energy level model (figure 6). Stable nuclides have an optimum number of protons and neutrons in their nuclei which minimises the energy of the nucleus. The other squares represent the radioactive nuclides, or *radionuclides.* These nuclides are unstable because they do not have the optimum combination of protons and neutrons. They will decay by one of several different processes, turning into different nuclides until they reach the line of stability.

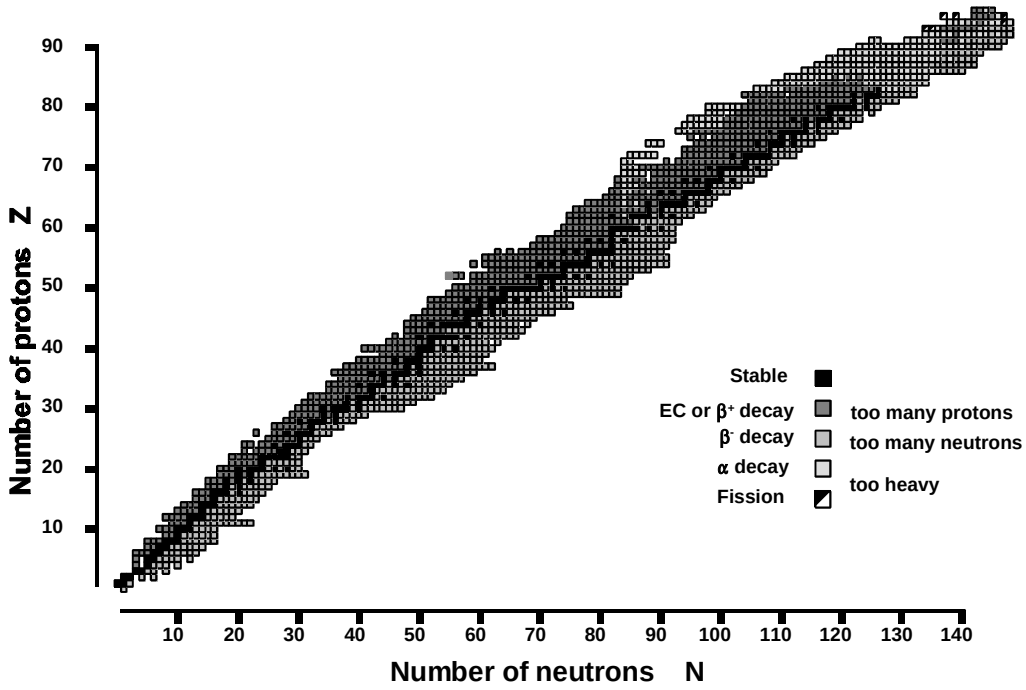


Figure 7 - Chart of the nuclides

Nuclides above and to the left of the line of stability have too many protons (as in figure 6b) and they decay either by *positron emission* (also known as *beta plus decay*) or by *electron capture*. Nuclides below and to the right of the line of stability have too many neutrons (as in figure 6c) and they decay by *electron emission* (also called *beta minus decay*). At the top right of the chart, nuclides are just too

heavy to be stable and they decay by either *alpha decay* or by *fission*. The chart of the nuclides can be thought of a bit like the contour map of a steep sided valley showing the route by which rocks will find their way down the hillside, loosing energy all the way until they reach the valley bottom.

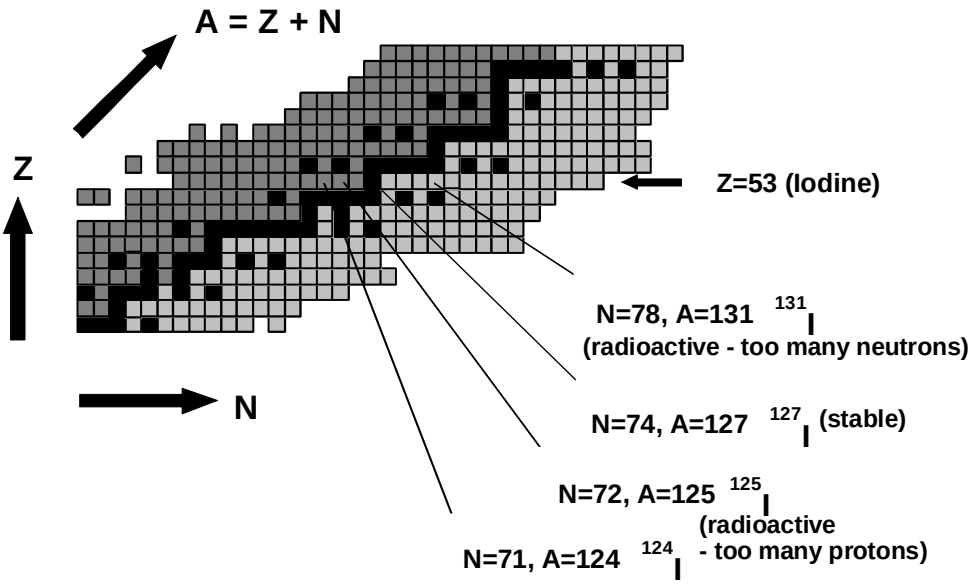


Figure 8 - Isotopes of Iodine

Figure 8 shows an expanded version of part of the chart of the nuclides. The row corresponding to Z=53 includes all the isotopes of iodine. There is only one stable isotope on this row, corresponding to N=74 which is ^{127}I. The nuclides ^{124}I and ^{125}I both lie above the line of stability and are radioactive because they have too many protons compared with the optimum. On the other hand ^{131}I lies on the other side of the line of stability and is radioactive because it has too many neutrons.

7.1 Electron Capture

A nuclide with too many protons can make its nucleus more stable by changing a proton into a neutron. One way in which this can be achieved is if the nucleus absorbs one of its orbiting electrons into the nucleus. This process is illustrated in figure 9. An atomic electron (negatively charged) from an inner orbit combines with one of the protons (positively charged) in the nucleus, to form a neutron (no charge) and a neutrino (no charge). This can be written as:

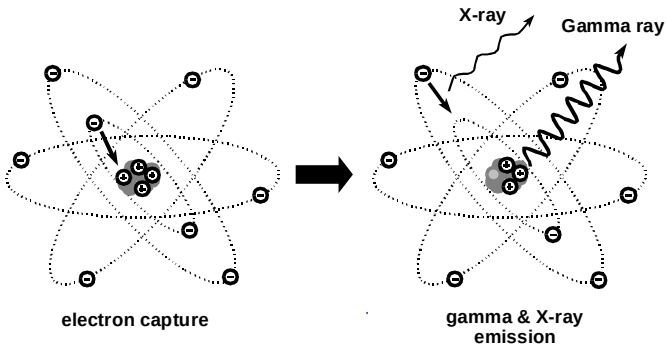


Figure 9 - Electron capture

$$p + e^- \rightarrow n + \nu$$

The net result for the atom is to reduce Z by 1 and increase N by 1 so there is no change in A, which is the sum of Z and N. However, because Z has changed, the atom has transmuted from one element into another. The neutrino which is emitted has no charge and negligible mass and is extremely unlikely to interact with anything else, so for most purposes it can be ignored in the decay.

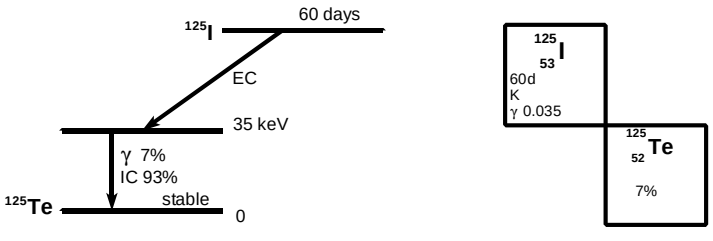
The process is called *electron capture* decay, or sometimes *K capture* because the captured electron comes from the innermost shell of orbiting electrons which is known as the K shell. After this has taken place there will be an electron missing from the K shell and so other electrons will immediately fall down to fill the vacancy, emitting characteristic X-rays as they do so. In the same way the swapping

of a proton for a neutron in the nucleus involves a change in the configuration of nucleons and the emission of the excess energy of the nucleus as gamma rays.

Iodine-125 is an example of a nuclide which decays by electron capture. We can write

$$^{125}_{53}\mathrm{I} \longrightarrow {}^{125}_{52}\mathrm{Te} + \text{neutrino} + \text{gamma ray} + \text{X rays}$$

This shows that an atom of iodine-125 with 53 electrons, 53 protons and 72 neutrons has decayed into tellurium-125 which has 52 electrons, 52 protons and 73 neutrons. In doing so it has released some energy from the nucleus as a gamma ray and also some energy from the atomic electrons as X-rays.



a) Decay scheme b) Nuclide chart

Figure 10 - Decay of Iodine-125

Figure 10a is a representation of this decay scheme in a format which is often used in reference books. Increasing nuclear energy levels are represented by distance up the diagram and increasing atomic numbers by distance to the right. The state at the top of the diagram representing ^{125}I has a half-life of 60 days. It decays by electron capture to ^{125}Te which is at a lower energy level and also further to the left on the diagram because the atomic number has decreased by one. The resulting state of the ^{125}Te nucleus has an energy 35 keV above the lowest possible energy level. A gamma ray with 35 keV of energy is then emitted, but in 93% of decays this is undergoes internal conversion and an internal conversion electron is emitted instead. This leaves the nucleus in its lowest energy, or ground state, which is stable.

Figure 10b represents the same data as it might appear on a detailed chart of the nuclides. The box representing ^{125}I shows that it has a half-life of 60 days (shown as 60d) and that it decays by electron capture (indicated by K standing for K capture) and emits a gamma ray of 35 keV (shown as 0.035 MeV). Electron capture decay always causes a reduction of Z by one and an increase in N by one, so the resulting nuclide will be the box one down and one to the right on the chart of the nuclides. This is found to be ^{125}Te which has no decay data shown because it is stable. The figure of 7% shown in this box is the natural abundance of the nuclide.

7.2 Electron Emission (Beta minus decay)

A nuclide with too many neutrons can get closer to stability by converting a neutron into a proton. To balance charge it must also emit an electron and, to balance energy, a neutrino. This process of *electron emission* is exactly the reverse of the process described in electron capture decay. It can be written as

$$n \rightarrow p + e^- + \bar{\nu}$$

where $\bar{\nu}$ is another sort of neutrino which, as before, can be ignored. The net result for the atom is to increase Z by 1 and decrease N by 1 so once again there is no change in A. The change in Z means that the atom has transmuted into the element with the next higher atomic number. This process is also called *beta minus decay* (or just beta decay for short) because the electron emitted is what is observed as a beta particle. As in electron capture decay, the resulting nucleus may emit its excess energy as one or more gamma rays. Note that, unlike electron capture decay, there are no atomic electrons involved in this decay and so there are not necessarily any X-rays emitted (although there might be some due to a subsequent process of internal conversion).

Iodine-131 is an example of a nuclide which decays by beta minus decay. We can write

$$^{131}_{53}\mathrm{I} \longrightarrow {}^{131}_{54}\mathrm{Xe} + \text{neutrino} + \text{beta particle} + \text{gamma ray}$$

Note that the atomic number has increased by one and so an iodine atom has changed into a xenon atom. In doing so it has emitted a beta particle and an undetectable neutrino and also released some energy from the nucleus as a gamma ray.

Figure 11a represents a simplified version of this decay scheme. The state representing ^{131}I has a half-life of 8 days and decays by beta decay to either of two states of ^{131}Xe. These are further to the right on the diagram because the atomic number has increased by one. The decay may either emit a beta particle with maximum energy of 606 keV, resulting in an excited state of the ^{131}Xe nucleus 364 keV above the ground state, or a beta particle with a maximum energy of 333 keV, resulting in a state at 637 keV above the ground state. These are the maximum beta particle energies. In practice the beta particles may have any energy between zero and this maximum, with a typical average being one third of the maximum. The remaining energy is carried away by the elusive neutrino, and this is why Pauli predicted that they must exist, even though they could not be detected. The excited states of ^{131}Xe immediately decay to the ground state, and in 82% of decays a gamma ray with 364 keV of energy is emitted and in 7% of decays a gamma ray of 637 keV. The remaining 11% of decays have other outcomes which have been omitted from this simplified version of the decay scheme for the sake of clarity.

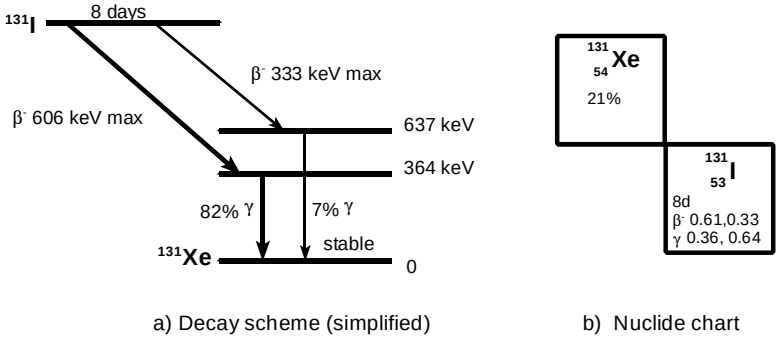


Figure 11 - Decay of Iodine-131

Figure 11b represents the same data as it might appear on a detailed chart of the nuclides. The box representing ^{131}I shows that it has a half-life of 8 days and that it decays by beta minus decay with maximum beta particle energies of 0.61 and 0.33 MeV (in decreasing order of probability). Gamma rays of 0.36 MeV and 0.64 MeV are also emitted. Beta minus decay always causes an increase of Z by one and a decrease in N by one, so the resulting nuclide will be the box one up and one to the left on the chart of the nuclides. This is found to be ^{131}Xe which is stable and has a 21% natural abundance.

7.3 Positron Emission (Beta plus decay)

In section 7.1 we have already considered electron capture as one sort of decay that may occur when a nucleus has too many protons. An alternative process which occurs in these type of nuclei is *positron emission*. In this process a proton changes into a neutron plus a positron and a neutrino:

$$\mathbf{p \rightarrow n + e^{+} + \nu}$$

This is very similar to ordinary beta decay except that the roles of proton and neutron are reversed and the emitted particle is positively charged instead of negatively. It is therefore sometimes called *beta plus decay*. As in the case of electron capture decay, the net result of positron emission is to reduce the Z of the atom by 1 and increase N by 1 so there is no change in A.

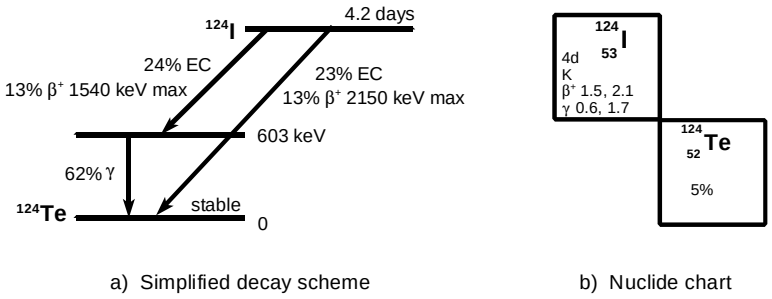
The emitted positron usually only travels a short distance in the surrounding material before it comes to a stop. Then, since it is the antiparticle of an ordinary electron, it will immediately annihilate with an electron from the surrounding material. The annihilation causes both the positron and the electron to disappear, but their energy, each equivalent to 511 keV (see section 4), cannot be destroyed. The energy is converted into two gamma rays, each of 511 keV energy, which fly off in opposite directions. This is called the *annihilation radiation*.

Iodine-124 is an example of a radionuclide which can decay by positron emission, although it only does this in about a quarter of decays; the rest of the time it decays by electron capture. We can write the positron emission decay mode as

$$^{124}_{53}\mathrm{I} \longrightarrow {}^{124}_{52}\mathrm{Te} + \text{positron} + \text{neutrino} + \text{gamma ray}$$

and then when the positron annihilates

$$\text{positron} + \text{electron} \longrightarrow \text{two 511 keV gamma rays}$$



a) Simplified decay scheme b) Nuclide chart

Figure 12 - Decay of Iodine-124

The decay scheme of iodine-124 is illustrated in figure 12. This shows that ^{124}I, with a half-life of 4.2 days, can decay to either an excited state of ^{124}Te, followed by emission of a 603 keV gamma ray, or directly to the ground state. 24% of decays are by electron capture to the 603 keV level and 23% by electron capture directly to the ground state. 13% of decays are by positron emission with a maximum beta plus energy of 1540 keV and another 13% by positron emission with a maximum beta plus energy of 2150 keV. The remaining 27% of decays are by electron capture to higher energy levels not shown on this simplified diagram, but most of these eventually decay down to the 603 keV level. Therefore, in total, 62% of decays result in emission of a 603 keV gamma ray and there are also other less abundant gamma ray emissions from the higher levels which are not shown. In total 26% of decays are by positron emission, each of which results in two annihilation gamma rays.

There are other nuclides, notably ^{11}C, ^{13}N, ^{15}O and ^{18}F, which decay purely by positron emission. These nuclides have particular medical applications in the technique of *positron emission tomography* (known as PET). This uses two or more detectors to detect the 511 keV annihilation gamma rays in coincidence. Because these were produced simultaneously and travel in almost exactly opposite directions, the annihilation event must have occurred somewhere along the straight line joining the two detection points. Because the positron from one of these decays only has enough energy to travel about 1 mm in tissue before it comes to a stop and annihilates, the location of the decaying atom must also have been very close to this straight line. The technique is therefore particularly suited to the location of radioactive isotopes of the biologically important elements carbon, nitrogen and oxygen within patients.

7.4 Parents and daughters

In all of the above examples of radioactive decay one nuclide has turned into another of a different element. The first nuclide is known as the *parent* and the one that it decays into is called the *daughter*. In the examples discussed so far, although the parent nuclide has been radioactive the daughter nuclide has been stable so that no further decay occurs. However, this is not always the case and sometimes the daughter nuclide is also radioactive. As Rutherford and Soddy discovered in their studies of radioactivity, this can lead to chains of several generations of radioactive nuclides before a stable one is reached.

A simple example of a parent with a radioactive daughter is strontium-90 which decays with a half-life of 28 years by electron emission (beta minus decay) into yttrium-90. This in turn has a half-life of 64 hours and also decays by electron emission into zirconium-90 which is stable. We can write this as

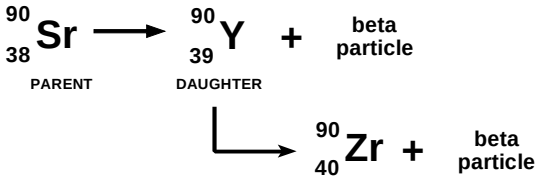
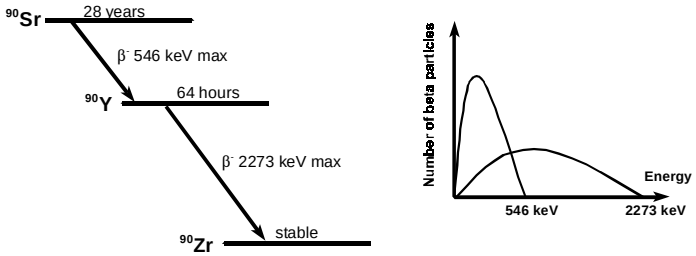


Figure 13a illustrates this decay scheme, where ^{90}Sr is the parent and ^{90}Y the daughter. Although the daughter has a shorter half-life than the parent it never manages to decay away completely because there are always new daughter atoms being created by decay of the parent. In fact an equilibrium is reached where, for each daughter atom lost by decay, a new one is gained by decay of the parent. Thus, at equilibrium, the number of disintegrations per second of the daughter is equal to the disintegrations per second of the parent. This means that the activity of the daughter is equal to the activity of the parent. A source of ^{90}Sr will therefore always have an equal activity of ^{90}Y included within it.



a) Decay scheme b) Beta particle energies

Figure 13 - Decay of Strontium-90

As shown in figure 13a the decay of the parent ^{90}Sr produces beta particles with a maximum energy of 546 keV. Decay of the daughter ^{90}Y produces beta particles with a maximum energy of 2,273 keV. Figure 13b shows the number of beta particles emitted as a function of their energy and demonstrates that the beta particles actually have a range of energies from zero right up to the maximum. A beta particle source like this has medical applications for external therapy because, as will be shown in section 8.2, the beta particles have a well defined range in tissue and so only tissues close to the source will be irradiated. The distribution of dose around the source will be determined by the numbers of beta particles at each energy, with the highest energy particles travelling further from the source.

7.5 Isomeric transition and metastable states

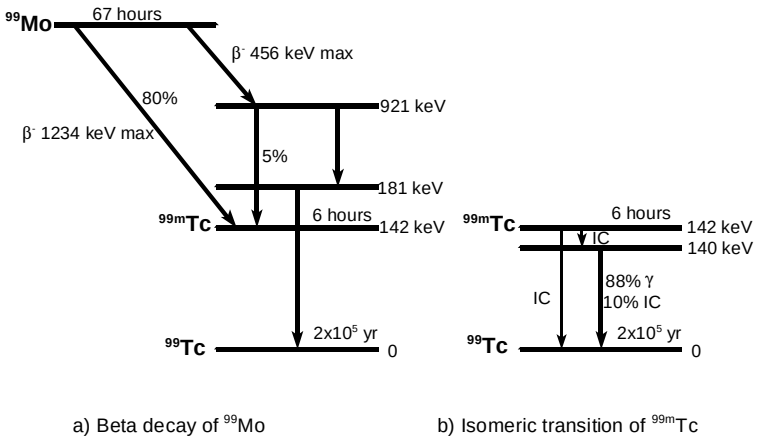
In all the examples of decay considered so far there has been a change in both Z and N. An *isomeric transition* is a decay that takes place without any change in Z or N. It corresponds to decay from an excited nuclear energy level as illustrated in figure 6d. On the chart of the nuclides (figure 7) this excited nuclear state may be imagined as if it were plotted in a third dimension perpendicular to the N and Z plane. An isomeric transition then involves a change into the plane of the paper which keeps the nuclide in the same square on the chart. An isomeric transition will result in the release of energy in the form of a gamma ray but without the emission of any other particles.

Nuclear transitions from an excited state are an integral part of other decay modes. For example the decay scheme of ^{131}I shown in figure 11a includes nuclear energy levels at 364 keV and 637keV which instantly decay down to the ground state. Because these transitions occur at the same time as the beta emission they are considered to be part of the same decay. Occasionally however an excited nuclear energy level may exist for an unusually long time; several seconds or even hours. When this happens the excited state is said to be *metastable* and it may be considered as a separate nuclide in its own right. This is done by adding the letter ‘m’ (for metastable) after its mass number. A metastable state can be imagined a bit like lying in bed in the morning. Although you know that you should get up and go downstairs as soon as the alarm rings, you tend to stay in bed for an unusually long time.

Once you overcome the barrier of actually getting out of bed, the rest is easy and you naturally stumble downstairs and get your breakfast. An atom in a metastable state is a bit like that; it is just waiting for enough of a nudge to overcome the barrier which will let it jump down to the ground state.

An example of a metastable state occurs in the decay of ^{99}Mo whose decay scheme is shown in figure 14a. ^{99}Mo has a half-life of 67 hours and decays by electron emission to ^{99}Tc. Some decays lead very quickly to the ground state of ^{99}Tc which has a very long half-life of 200,000 years and so on a human scale is near enough stable for its activity to be ignored. However, one of the excited states of the ^{99}Tc nucleus, with an energy 142 keV above the ground state, is metastable with a half-life of 6 hours. About 85% of ^{99}Mo decays leave the nucleus in this metastable state which is referred to as ^{99m}Tc.

Because ^{99m}Tc has a half-life long enough for it to exist in its own right we can show its decay scheme separately as in figure 14b. This is a good example of isomeric transition. In about 2% of decays the 142 keV energy level decays directly to the ground state of ^{99}Tc but this transition is always internally converted (see section 6.2) so only an internal conversion electron is emitted and no gamma rays. In 98% of decays the nucleus first moves to an energy level at 140 keV, which once again happens by internal conversion. This energy level decays to the ground state and in 10% of decays is internally converted so that in 88% of decays a 140 keV gamma ray is emitted. Apart from a small number of low energy internal conversion electrons this decay results in almost pure gamma ray emission with a single energy (monoenergetic) gamma ray. This makes ^{99m}Tc an extremely useful radionuclide for diagnostic imaging in nuclear medicine. Moreover, despite its short half-life of 6 hours, a plentiful supply of ^{99m}Tc is always available from the decay of its parent ^{99}Mo. A generator containing ^{99}Mo will soon build up an equal activity of ^{99m}Tc. Because they are different elements, the daughter Tc can be separated from the parent Mo chemically, using the fact that Tc is soluble in saline solution whereas Mo is not.



a) Beta decay of ^{99}Mo b) Isomeric transition of ^{99m}Tc

Figure 14 - Decay of Molybdenum-99

7.6 Alpha decay and fission

Nuclides at the extreme top right corner of the chart of the nuclides are unstable because they are just too heavy. The nuclear force which holds the nucleus together is very short range. Adding too many nucleons to the nucleus means that the individual nucleons are too far apart for the nuclear force to be able hold them together and the repulsive electrostatic force between the protons wins out. In this case one of two things can happen.

In *alpha decay* a group of two protons and two neutrons are ejected from the nucleus. These particles are held together by the nuclear force in a very stable group which is known as an *alpha particle*. It happens that this grouping of two protons and two neutrons also forms the nucleus of a helium atom

so alpha particles are actually doubly ionised (2 electrons removed) helium atoms. Alpha decay results in a reduction of Z by 2 and a reduction of N by 2 and so alpha decay moves a nuclide down two places and left two places in the chart of the nuclides. Many of the naturally occurring radionuclides investigated by Rutherford and Soddy exhibited alpha decay but alpha emitting nuclides have no medical applications.

Nuclear fission is an alternative decay mode for heavy nuclides in which the nucleus splits up into two more or less equal fragments. This is the process from which nuclear power is generated, but radionuclides which undergo fission have no direct medical use. However two useful radionuclides which we have already mentioned, ^{131}I and ^{99}Mo, are both abundant fission fragments from the fission of ^{235}U. They just have to be separated out from all the other radioactive fission fragments in nuclear waste.

8 Interaction of radiation with matter

Alpha particles, beta particles, gamma rays and X-rays are examples of *ionising radiation* which are so called because as they pass through matter they pass some of their energy to the atoms of the material, resulting in electrons being knocked out of the atom, the process of *ionisation*, or raised to higher energy levels, *excitation*. Sometimes this effect is harmful (for example causing damage to living cells) but sometimes it is the basis by which the radiations can be usefully detected. It is therefore important to understand the different ways in which these radiations interact in order to appreciate their uses and hazards.

8.1 Alpha particles

Figure 15 illustrates the passage of an alpha particle through matter. Because alpha particles (made up of 2 protons and 2 neutrons) are comparatively heavy and doubly charged, they cause a great deal of ionisation as they collide with atomic electrons in the material, knocking them out of their atoms. Because they are so much heavier than an electron they do this without deviating from a straight path, but each collision results in a small loss of energy to the alpha particle, so that it steadily slows down. The density of ionisation tends to increase towards the end of the particle's path. Occasionally an alpha particle may suffer a collision with an atomic nucleus, but this is comparatively rare because the nucleus is so small. However if an alpha particle does hit a nucleus it will be deviated significantly from its forward path and will also send the nucleus recoiling in a different direction. The recoil nucleus can then go on to cause additional ionisation in the material.

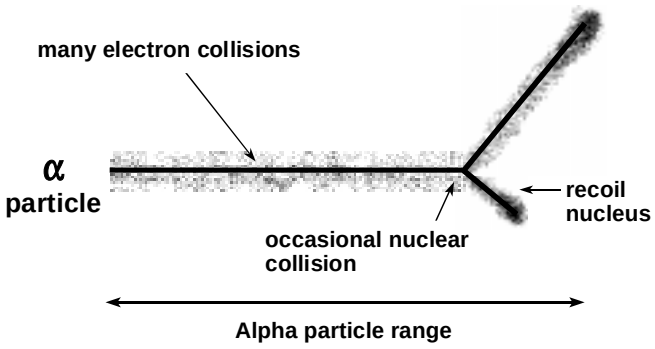


Figure 15 - Alpha particle interaction with matter

Because the ionisation produced is so dense, the alpha particle will soon lose all its energy as a result of many electron collisions and rapidly come to a stop. The distance travelled before it finally stops is called the particle's *range*. The range depends on the particle's energy and the material through which it travels, but for an alpha particle it is always very short. For example an alpha particle with an energy of 1 MeV will have a range of 5 mm in air and only 7 microns in tissue. From this it is clear that an alpha particle source outside the body will do little harm, because all the alpha particles will be absorbed in the superficial layers of the skin which are dead anyway. However if an alpha source was allowed to get inside the body its radiation would be absorbed in a few cells and could produce very damaging effects. This is why alpha emitting radionuclides, such as ^{238}Pu, are so dangerous if inhaled. Alpha emitters are not used in medicine.

8.2 Beta particles

Figure 16 illustrates the passage of a beta particle through matter. Because beta particles (electrons) are lighter and only singly charged, they produce less dense ionisation than alpha particles and are much more easily deviated from a straight line as they ionise atoms in the material through which they pass. Frequently the collisions with an atomic electron are sufficiently violent to cause the beta particle to deviate through a large angle and then the atomic electron with which it collided acquires enough energy to move off on its own. This electron is called a *delta ray* and it goes on to produce further ionisation. Occasionally, if a beta particle happens to encounter an atomic nucleus in a material of high atomic number, it will be deviated very violently and in doing so gives off *bremsstrahlung X-rays* (from the German for breaking radiation).

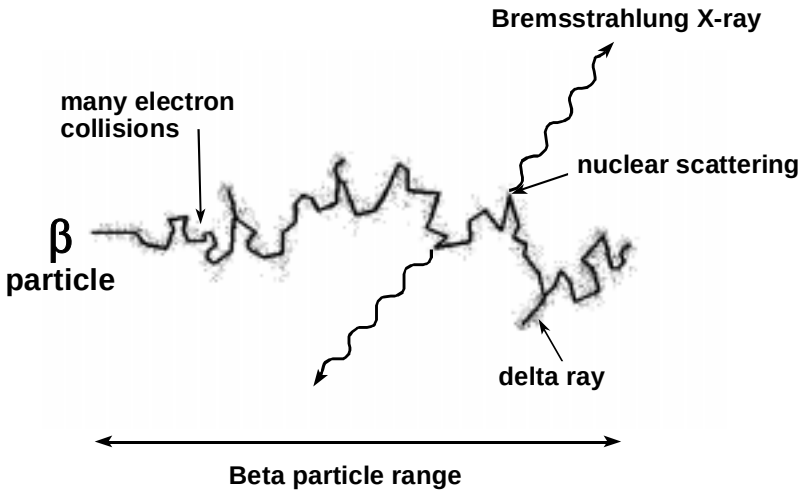


Figure 16 - Beta particle interaction with matter

After a very zig-zag track, beta particles will eventually come to rest and so, like alpha particles, they exhibit a definite range. However, since they produce less dense ionisation, they slow down more gradually than alpha particles and will have a longer range. For example, 600 keV is a typical beta particle energy; this is the maximum energy of beta particles from ^{131}I decay and the average energy from decay of ^{90}Sr and its daughter ^{90}Y. A 600 keV beta particle has a range of 2.5 metres in air or 3 mm in tissue. Because all beta sources emit a range of beta particle energies, rather than just a single energy, there will always be a spread in the range of particles emitted. The number of beta particles therefore falls off quite rapidly with thickness of material traversed, until none remain after a thickness equal to the range of the maximum energy present.

If a beta source is close to, or even inside, the body its radiation will be absorbed within a few millimetres of the source. This means that all the energy is absorbed in local tissues and, since beta particles are moderately ionising, there is potential for damaging effects to these tissues. In diagnosis this may be looked upon as a hazard to be minimised, but it can be put to good use in therapeutic applications. For example the high energy beta particles emitted from the decay of ^{90}Sr (and its daughter ^{90}Y) can be used in an external applicator for therapeutic doses to surface tissues. The beta particles from ^{131}I are also used in therapy of the thyroid. Since iodine is concentrated by thyroid tissue a patient administered with radioactive iodine ^{131}I will receive a larger radiation dose to the thyroid than to other organs.

Nuclides such as ^{3}H, which emit low energy beta particles, result in a smaller radiation dose which means that, in small amounts, they may be safely administered internally for *in-vivo* diagnostic studies. However, since the beta particles will not escape from the patient, measurements of the activity present must be made by collecting blood or urine samples and then counting these in the laboratory. Even then detecting the low energy beta particles is not easy and the samples must be intimately mixed with the detecting medium in a liquid scintillation counter. Slightly higher energy beta particles, such as those from ^{35}S, are useful for autoradiography. When tissue containing ^{35}S is placed on a photographic film, the beta particles will only blacken the film locally, producing an image of the activity distribution in the sample.

8.3 Gamma rays and X-rays

Gamma rays and X-rays are not particles like alpha and beta, but are examples of *electromagnetic radiation* (like high energy light) and consequently interact with matter in a rather different way. Figure 17 illustrates the passage of several gamma rays through matter. Unlike alpha and beta, where each particle undergoes many individual interactions, each gamma ray only encounters one, or possibly two, interactions and many gamma rays pass through with no interaction at all.

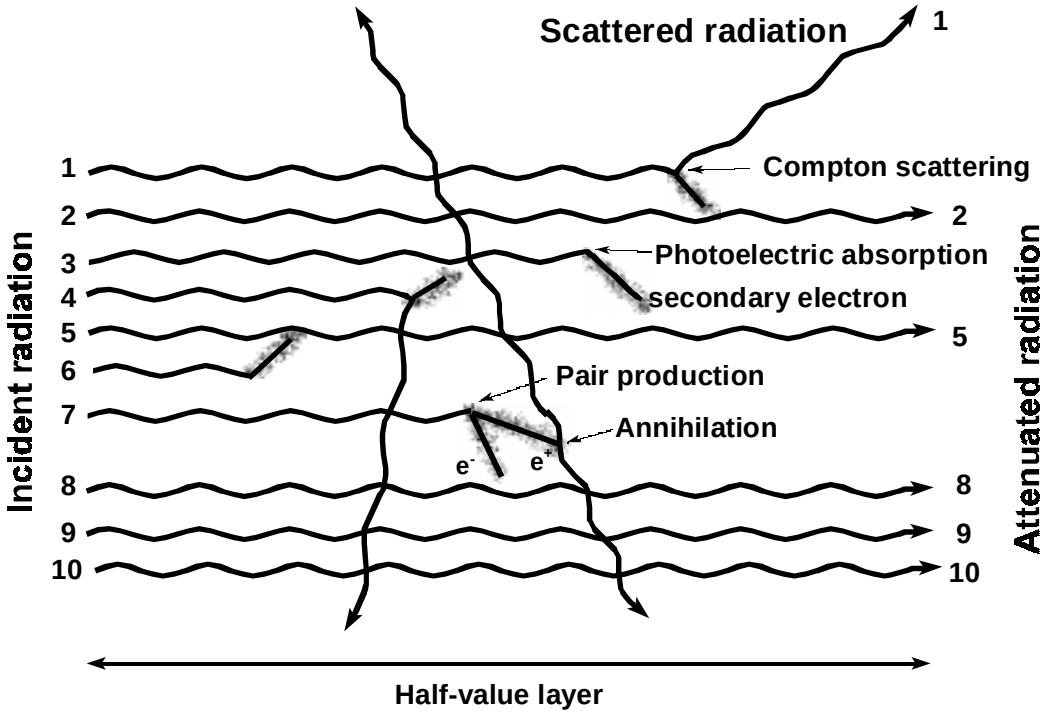


Figure 17 - Gamma ray interaction with matter

Gamma rays and X-rays do not produce ionisation directly, but instead they do so by first producing *secondary electrons*. These arise from two types of process; *scattering* and *absorption*. Scattering occurs through the process of *compton scattering* in which a gamma ray interacts with a free electron in the material. The gamma ray passes some of its energy to the electron and continues on its way as scattered radiation with a lower energy and travelling in a different direction (for example rays 1 and 4 in figure 17). There are two possible absorption processes in which the gamma ray disappears altogether. *Photoelectric absorption* occurs when a gamma ray gives up all of its energy at once to an atomic electron which is then ejected from the atom (rays 3 and 6 in figure 17). Gamma rays with energy greater than 1 MeV can also be absorbed by *pair production,* in which an electron and positron pair are spontaneously produced (ray 7 in figure 17). The positron will subsequently annihilate with an atomic electron producing two gamma rays of 511 keV. After any of these processes the secondary electrons produced go on to produce ionisation of the material, just like a beta particle.

Unlike alpha and beta particles, which are stopped after many interactions, gamma rays and X-rays each undergo only a few interactions. Gamma rays do not therefore have a definite range, but instead the intensity of a gamma ray beam is *attenuated* by a combination of scattering and absorption processes so that it falls off steadily with distance. The distance required to halve the number of the gamma rays is called the *half-value layer* (HVL). This is analogous to the half-life of radionuclide decay and the same exponential mathematics apply. In figure 17 the incident radiation consists of ten gamma rays entering at the left. During passage through one half value layer of the material 3 of these are absorbed and 2 scattered leaving an attenuated beam containing only 5 gamma rays. In the next half value layer, half of these would again disappear. The half value layer depends on the energy of the radiation and the nature of the material. For a gamma ray of 140 keV the HVL in lead is 0.25 mm. Therefore 0.25 mm of lead shielding will reduce the intensity of 140 keV radiation to half its

original value, 0.5 mm will reduce it to one quarter, 1 mm (4 HVLs) to one sixteenth and 3 mm (12 HVLs) by a factor of 1/4096.

In tissue the HVL is much greater, being 47 mm for 140 keV gamma rays. Thus if a radionuclide such as ^{99m}Tc, which emits 140 keV gamma rays, is present inside a person it is clear that sufficient numbers of gamma rays will be able to penetrate body tissues to permit external detection of the whereabouts of the radionuclide for diagnostic imaging purposes. Gamma rays that do not escape will distribute their energy throughout several organs, leading to a distributed radiation dose which is much less damaging than the local doses from beta emitters. This is why pure gamma emitting radionuclides such as ^{99m}Tc are so useful for diagnostic imaging purposes.

9 Radiation dose

When ionising radiations (alpha, beta, gamma or X-rays) pass through matter they pass on some or all of their energy to the material by ionising and exciting the atoms of the material through the processes described above. The damage done by this depends both on the energy deposited and the amount of material involved. The radiation damage increases as the amount of energy deposited increases and decreases if it is spread throughout a greater amount of material. The radiation *absorbed dose* is therefore defined as the energy absorbed divided by the mass of material involved. One Joule of energy absorbed in each kilogram of material is defined as an absorbed dose of one gray (written 1 Gy). Usually we are dealing with doses smaller than this so we use units of one thousandth of a gray, or one milligray (written 1 mGy).

The concept of absorbed dose applies to all types of material but, when we need to assess the effect on biological tissues, we also need to take account of the fact that some types of radiation are more harmful than others. For example, because they are so densely ionising, alpha particles are about twenty times as effective at killing cells as beta particles, gamma rays or X-rays. Therefore when measuring the dose to biological tissues we use a quantity called *equivalent dose* which is defined as the absorbed dose multiplied by a radiation weighting factor. This radiation weighting factor is 20 for alpha particles but 1 for beta particles, gamma rays and X-rays. Confusingly, although equivalent dose has essentially the same units as absorbed dose, it is given a different special name of the sievert (written Sv) or millisievert (mSv). Since we never have to deal with alpha particles in medical applications it happens that the equivalent dose (in Sv or mSv) is always numerically the same as the absorbed dose (in Gy or mGy).

There is one final complication to measuring the effect of radiation on a person; not all tissues in the body are equally sensitive to radiation damage. For example the bone marrow is particularly susceptible to damage whereas the skin is relatively insensitive. Therefore, in situations where different parts of the body might receive different doses, it is usual to calculate a weighted sum of the equivalent doses to each organ. The organ weighting factors take account of the susceptibility of each organ to damage. Thus bone marrow gets a larger weighting factor than skin. This weighted sum of organ doses is called the *effective dose*. Because the weighting factors for all organs in the body add up to one, if every organ receives the same equivalent dose the effective dose will be the same as the equivalent dose. Therefore the effective dose can be thought of as the uniform whole body dose which would have the same effect (in terms of the risk of doing harm) as the actual non-uniform dose. Effective dose is measured in units of sievert (Sv) or millisieverts (mSv) just the same as equivalent dose.