# RADIATION PROTECTION NOTE 1: RADIOACTIVITY BASICS

## INTRODUCTION

An understanding of the underlying principles involved in the radioactive decay process is essential for the safe working and handling of radioactive materials. This first ‘Note’ introduces the basic physics involved.

## THE ATOM

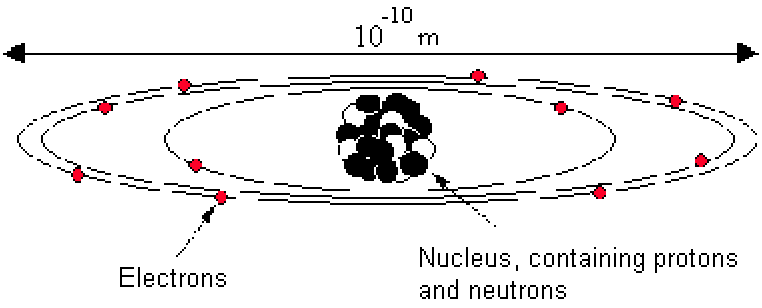



*Fig 1: Structure of a Typical Atom*

All matter is composed of atoms; the structure of a typical atom is shown in figure 1. Atoms are made up of three particles, which we call protons, neutrons and electrons. Table 1 gives some of the characteristics of each particle.

| Particle | Charge | Mass | Applicable Forces | Position in Atom |
|---|---|---|---|---|
| proton | +1 | 1 amu * | Coulombic, strong & weak nuclear | nucleus |
| neutron | 0 | 1 amu | strong & weak nuclear | nucleus |
| electron | -1 | 0.00055 amu | Coulombic | orbital shell |

*Table 1: some characteristics of the fundamental particles*
** amu = atomic mass unit, 1 amu ~ 1.7x10$^{-27}$ kg*

The nucleus is at the centre of the atom and consists of approximately equal numbers of protons and neutrons and almost the entire mass of the atom. The diameter of the atom is of the order $10^{-10}$m and the nucleus $10^{-14}$m. Electrons exist outside of the nucleus in discrete orbits, sometimes called ‘shells’.

Atoms are arranged in the Periodic Table in order of increasing numbers of protons and are characterised by the symbol ${}^{A}_{Z}X$ [1]. Atoms that share the same physical and chemical characteristics are called elements eg, all atoms of the element Oxygen are characterised by the symbol ${}^{16}_{8}O$ . It is possible for atoms of the same element to have a different number of neutrons and we call these atoms isotopes of the element. Isotopes can be stable or unstable eg, ${}^{18}_{8}O$ is a stable isotope of Oxygen but ${}^{32}_{15}P$ is an unstable isotope of the element Phosphorous ${}^{31}_{15}P$ .

From Table 1 we see that protons and electrons are (oppositely) charged particles, each carrying an electrical charge of 1 (by convention protons are positively charged and electrons negatively charged). Inside the nucleus, the electrostatic repulsion between neighbouring protons is balanced by the strong attractive nuclear force which exists between all nucleons (‘nucleon’ is the term used to describe protons and neutrons).

For light elements, this balance or ‘stability’ is achieved when the number of protons is approximately the same as the number of neutrons (n:p ~ 1:1) but as we proceed through the periodic table to heavier elements, we find that a higher ratio of neutrons is required for stability (n:p ~ 1.6:1).

It may also be the case that atomic stability is reached with differing numbers of neutrons for the same element and these are called stable isotopes of the element. Atoms that do not satisfy the criteria for nuclear stability are said to be unstable.  Stability, the lowest energy state, can be achieved by one or more of the following radioactive decay processes.

### β MINUS DECAY

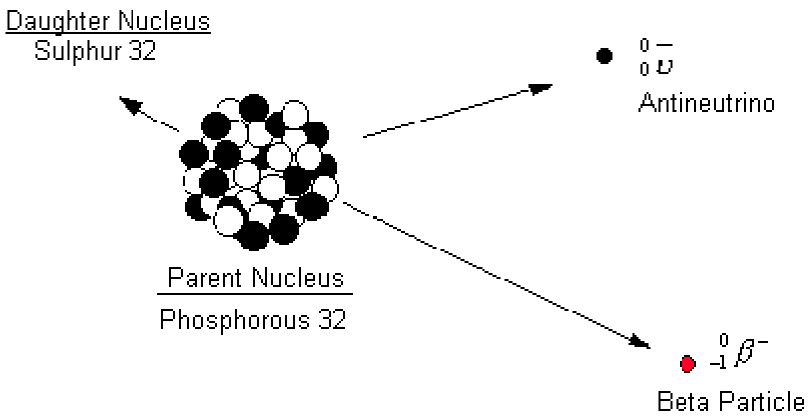



*Fig 2: An example of $\beta^-$ decay*

The atom phosphorous 32 ($^{32}_{15}P$) is an unstable isotope of phosphorous 31 ($^{31}_{15}P$). Its nucleus contains 15 protons and 17 neutrons ie, it has excess neutrons. It regains stability (fig. 2) by transforming[2] the excess neutron into a proton to form the stable isotope sulphur 32 ($^{32}_{16}S$). During this process, two fundamental laws of physics have to be satisfied: Conservation of Energy and Conservation of Charge.  These are satisfied by the emission from the ‘parent’ nucleus of a negatively charged electron and a chargeless, virtually massless particle called an antineutrino. Symbolically:

$$^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^- + \bar{\upsilon}$$

The ejected electron is historically called a beta (minus) particle and in reaching stability there is a surplus of energy that is shared in varying amounts between the beta particle and the antineutrino. This means that the beta particle is ejected from the parent nucleus with a range of energies from zero to a well-defined maximum.

### β PLUS DECAY

In the above example the $^{32}_{15}P$ atom has an excess neutron, but what happens when an atom has an excess of protons? Figure 3 shows the atom $^{19}_{10}Ne$ which has 10 protons and 9 neutrons. Stability is reached through a process similar to that of beta minus decay. The excess proton is transformed into a neutron[2] with the emission, from the nucleus, of a positively charged electron, called a positron, and a neutrino. The positron is the anti-particle of the electron. As with beta minus decay, surplus energy is shared between the positron and the neutrino with the positron exhibiting a range of energies up to a well-defined maximum.

A consequence of the matter-antimatter relationship between the positron and the electron is that the emitted positron will soon encounter a ‘normal’ electron.  When this happens, both particles will ‘annihilate’ each other with a release of 0.511 MeV of energy for each particle. This annihilation radiation always accompanies beta plus decay.

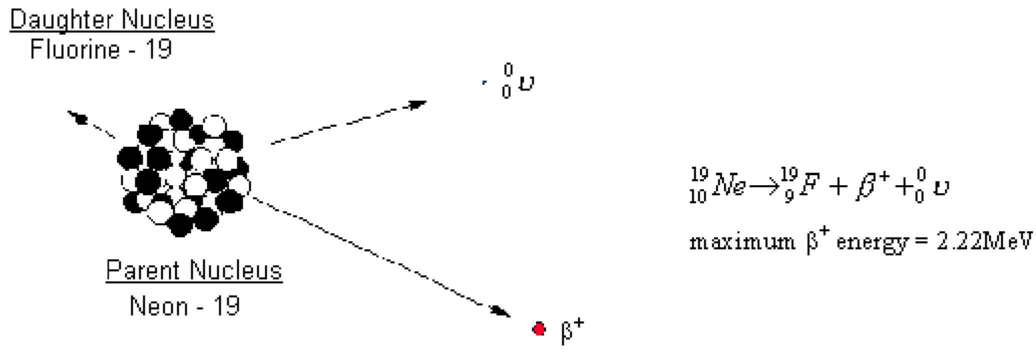



*Fig 3: Example of beta plus decay, maximum $\beta^+$ energy = 2.22MeV*
*Annihilation energy is $2(m_e c^2)$ = 1.022 MeV*

Symbolically:

$${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + \beta^+ + {}^{0}_{0}\upsilon + annihilation\ radiation$$

**ELECTRON CAPTURE**

Atoms with excess protons can achieve stability through an alternative process to that of $\beta^+$ decay. This occurs when an orbital electron**[3]** is pulled into the nucleus and combines with a proton to form a neutron - we say that the electron has been 'captured'. The only particle emitted by the nucleus in this case is a neutrino. Typically, the nucleus is left with an excess of energy ie, it is said to be in an 'excited' state and it releases this energy by emitting gamma radiation**[4]**.

A consequence of the capture process is that an inner orbital electron has been removed from the atom leaving a vacancy. This vacancy is quickly filled by a higher orbital electron 'dropping down' and is accompanied by the emission, from the atom, of electromagnetic radiation (typically X-rays) which is characteristic of the two orbitals involved**[5]**. Symbolically:

$${}^{A}_{Z}X + e \rightarrow {}^{A}_{Z-1}Y + \upsilon + \nu(X - rays) + \gamma(possibly)$$

An example of a radioisotope commonly used in the laboratory is ${}^{125}_{53}I$ .

$${}^{125}_{53}I \rightarrow {}^{125}_{52}Te + 0.027MeV(X - rays) + 0.035MeV(\gamma - rays)$$

**GAMMA EMISSION**

Following radioactive decay, it is common for the daughter nucleus to be left in an excited state with excess energy. This energy is rapidly (~ $10^{-14}$s) released as electromagnetic radiation, because the radiation originates from the nucleus it is given the name gamma *($\gamma$)* radiation.

Figure 4 shows an example of a radioactive decay process involving the emission of gamma radiation. A point to note is that there are no pure gamma emitters: gamma radiation only occurs if the daughter nucleus is left in an excited state following some other form of decay process.

Accompanying the decay of ${}^{60}_{27}Co$ (figure 4) to ${}^{60}_{28}Ni$ is the emission of two gamma-ray photons of characteristic energy 1.17 MeV and 1.33 MeV. This is a consequence of the nucleons in the nucleus occupying quantised energy levels**[5]**.

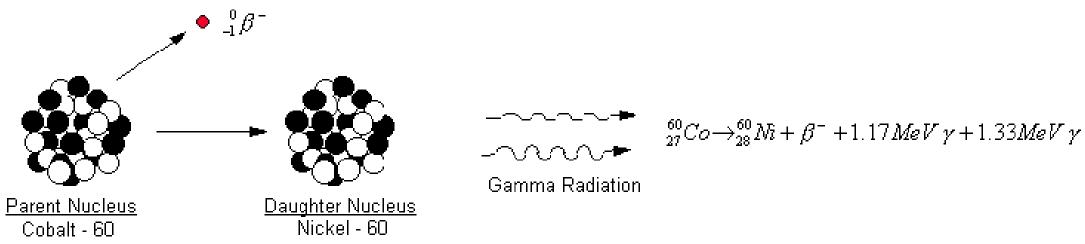



*Fig 4: An example of radioactive decay involving the emission of gamma radiation. A consequence of the quantisation of the nucleus is that the emitted gamma-ray photons from a particular nucleus have a unique gamma-ray spectrum*

**ALPHA DECAY**

Alpha ($\alpha$) decay is the emission from the nucleus of a tightly bound arrangement of two protons and two neutrons ($^{4}_{2}He$ - a helium nucleus) and is the result of spontaneous fission of an unstable heavy nucleus (Z > 82). Figure 5 shows an example of $\alpha$-decay.

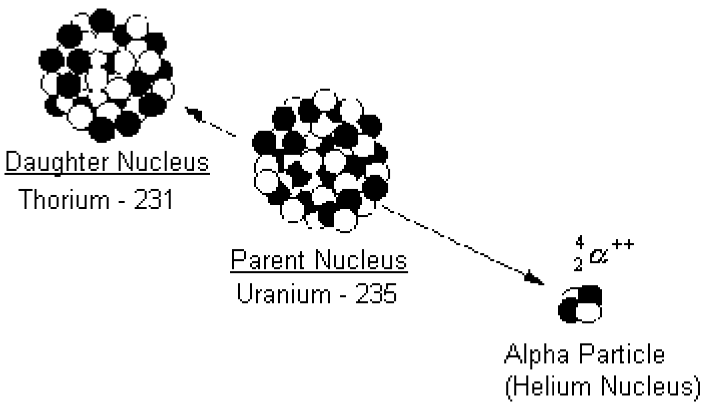



*Fig 5: Spontaneous fission of $^{235}_{92}U$, with the emission of an $\alpha$ - particle.*

Symbolically: $^{A}_{Z}X \rightarrow ^{A-4}_{Z-2}Y + \alpha$

The alpha particles emitted are monoenergetic and generally have an energy of ~ 5 MeV.

**THE RADIOACTIVE DECAY EQUATION**

The laws of probability govern the decay of radioactive nuclei and we cannot say with any certainty when a particular nucleus will disintegrate. What we can say is, for any particular radioisotope, the rate of disintegration is proportional to the number of original atoms present. Symbolically:

$$\frac{dN}{dt} = -\lambda N \qquad (1)$$

Where:
dN/dt is the rate of change of quantity N with respect to time.
$\lambda$ is called the decay constant, defined as the instantaneous fraction of atoms decaying per unit time and is unique for each radionuclide. The minus sign indicates that the quantity is decreasing.

The solution to this equation is given as[6]:

$$N_t = N_0 e^{-\lambda t} \qquad (2)$$

Where:
$N_t$ is the number of nuclides remaining at time *t*.
$N_0$ is the original number of nuclides.
The form of equation (2) indicates that the number of nuclei present at time *t* decreases exponentially with time and this introduces the concept of half-life as shown in figure 6.

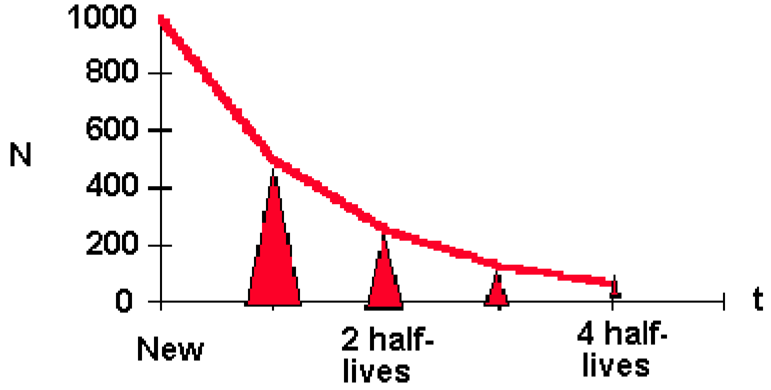



*Fig 6: Time required for amount of radioactive material to decrease by one-half is called the half-life*

The half-life of a radioisotope is given the symbol $\tau_{½}$. Re-arranging equation (2) gives the following useful formula for the half-life:

$$\tau_{1/2} = \frac{0.693}{\lambda} \qquad (3)$$

Figure 6 shows the principle in action. If we start with 1000 nuclei, then after one half-life there will be 500 nuclei left, after two half-lives there will be 250, after three half-lives there will be 125 left and so on. The half-life principle applies to all radioisotopes and a conversion table is printed at the end of this Note.

## INVERSE SQUARE LAW

The decay of a radionuclide is isotropic. This means there is no preferred direction in which the radiation will be emitted. The consequence of this behaviour is that the decay of radioisotope material follows the inverse-square law[7]. In words, the inverse-square law says the flux of radiation is inversely proportional to the distance squared. Symbolically:

$$F = \frac{N}{4\pi d^2} \qquad (4)$$

Where:
F is the number of particles or photons crossing unit area.
N is the total number of particles or photons emitted.
d is the distance from the source.

The important point from equation 4 is that doubling the distance from a small source will reduce the dose received by a factor of four.

## UNITS

The rate of disintegration of a source is called the activity of the source. The SI unit of activity is the becquerel and is named after the discoverer of radioactivity Antoine Henri Becquerel (1852–1908).

1 becquerel (Bq) = 1 disintegration per second.

The becquerel is a small unit and activities are more often quoted in terms of kilobecquerels (kBq), megabecquerels (MBq) and so on.

Where:

1 kBq = $10^3$ Bq
1 MBq = $10^6$ Bq
1 GBq = $10^9$ Bq

etc

The previous unit of activity is the curie (Ci), with the conversion

1 Ci = $3.7 \times 10^{10}$ Bq = 37 GBq
1 mCi = 37 MBq
1 μCi = 37 kBq

Another useful conversion is 1 MBq ~ 27 μCi

**DECAY ENERGY**

The SI unit of energy is the Joule (J). In terms of the energy released as part of the decay process then the Joule is a very large unit and we normally use the unit 'electron volt[8]' (eV) where:

1 eV = 1.602 x $10^{-19}$ J

Nuclear decay energies are most often of the order $10^3$ and $10^6$ eV, i.e. keV and MeV

**Notes:**

**1** In the symbol ${}^{A}_{Z}X$ , A (atomic mass) = no. of protons + no. of neutrons, Z (atomic number) = no. of protons and X = the chemical symbol of the element. For an electrically neutral atom no. of protons = no. of electrons.

**2** The transformation occurs via a fundamental force called the weak interaction, this is beyond the scope of this course.

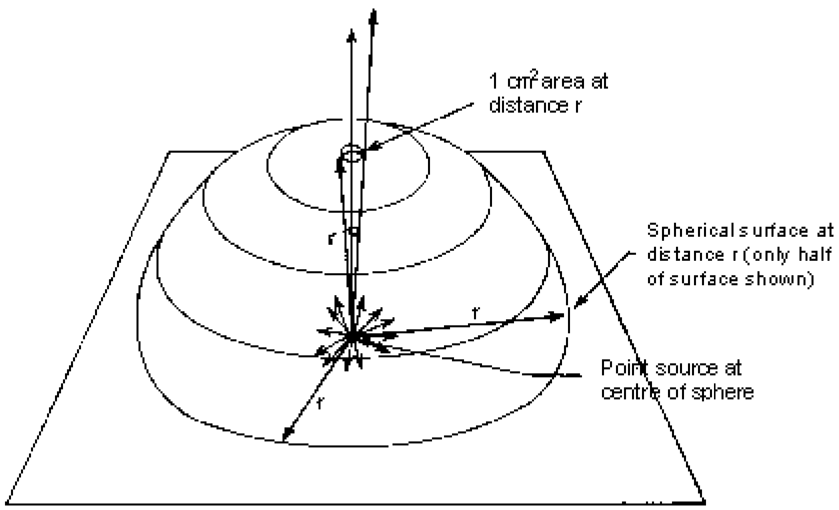
**3** Electrons are said to orbit the nucleus in discrete orbits called shells. Historically these shells were called k, l, m etc. You may see references in books to k-capture which means that an electron from the k-shell (innermost) has been captured by the nucleus.

**4** Nucleons in the nucleus are said to be quantised in a manner analogous to electrons. This means that the nucleus has discrete energy levels. After radioactive decay, a nucleon may be raised to a higher energy level. After a short period of time (typically $10^{-14}$ s) the nucleon will release this excess energy as a photon and return to the ground state. The released energy is characteristic of the energy levels involved and can be used to identify the emitting element. As the energy is emitted from the nucleus it is given the special name of gamma radiation.

**5** Symbolically: $h\upsilon = E_i - E_j$ ; where $E_i$ is the energy of the ith level.

**6** For the full worked solution to this equation see the end of this note.

**7** Emissions from an isotropic emitter will cover the surface of an expanding sphere of radius r. The surface area of a sphere is given by $4\pi r^2$




If the source emits N particles/photons then for any unit area on the surface of the sphere the number of particles or photons crossing the area is $N/4\pi r^2$.

**8** The electron volt is defined as the amount of energy required to move one electronic charge (e = 1.602 x $10^{-19}$ Coulomb) through a potential difference of one volt.

## SOME PROPERTIES OF RADIOISOTOPES IN COMMON USE

| Radioisotope | Half-life | Decay Mode | Radiation (MeV) | Hazard |
|---|---|---|---|---|
| Tritium - $^{3}H$ | 12.3 y | $\beta^-$ | 0.018 | Inhalation; Tritiated water |
| Carbon 14 – $^{14}C$ | 5760 y | $\beta^-$ | 0.159 | Inhalation; Radioactive $CO_2$ |
| Sulphur 35 – $^{35}S$ | 87 d | $\beta^-$ | 0.167 | eyes/skin |
| Phosphorous 32 - $^{32}P$ | 14.3 d | $\beta^-$ | 1.709 | eyes/skin |
| Phosphorous 33 - $^{33}P$ | 25.4 d | $\beta^-$ | 0.249 | eyes/skin |
| Chromium 51 - $^{51}Cr$ | 27.8 d | EC | 0.323 $\gamma$<br>0.005 X | Irradiation |
| Iodine 125 – $^{125}I$ | 60 d | EC | 0.035 $\gamma$<br>0.027 X | Inhalation<br>Irradiation |
| Iodine 131 – $^{131}I$ | 8 d | $\beta^-$ | 0.25 $\beta$<br>0.33 $\beta$<br>0.61 $\beta$<br>0.28 $\gamma$<br>0.36 $\gamma$<br>0.64 $\gamma$ | Inhalation<br>Irradiation |
| Technetium 99m – $^{99m}Tc$ | 6 h | IT | 0.002 $\gamma$<br>0.141 $\gamma$ | Irradiation |

EC = Electron Capture
IT = Isomeric Transition, transition involving a metastable nuclear state.

## TABLE OF VALUES FOR $(½)^n$

| n | 0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 |
|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1.000 | 0.933 | 0.871 | 0.812 | 0.758 | 0.707 | 0.660 | 0.615 | 0.578 | 0.536 |
| 1 | 0.500 | 0.467 | 0.435 | 0.406 | 0.379 | 0.354 | 0.330 | 0.308 | 0.287 | 0.268 |
| 2 | 0.250 | 0.233 | 0.217 | 0.203 | 0.190 | 0.177 | 0.165 | 0.154 | 0.144 | 0.134 |
| 3 | 0.125 | 0.117 | 0.109 | 0.102 | 0.095 | 0.088 | 0.083 | 0.077 | 0.072 | 0.067 |
| 4 | 0.063 | 0.058 | 0.054 | 0.051 | 0.047 | 0.044 | 0.041 | 0.039 | 0.036 | 0.034 |
| 5 | 0.031 | 0.029 | 0.027 | 0.025 | 0.024 | 0.022 | 0.021 | 0.019 | 0.018 | 0.017 |
| 6 | 0.016 | 0.015 | 0.014 | 0.013 | 0.012 | 0.011 | 0.010 | 0.010 | 0.009 | 0.008 |
| 7 | 0.008 | 0.007 | 0.007 | 0.006 | 0.006 | 0.006 | 0.005 | 0.005 | 0.005 | 0.004 |

Note: n is the number of half-lives or half-value layers. In 2.6 half-lives, the activity will be reduced to 0.165 of the initial amount. In 2.6 half-value layers, the dose rate will be reduced to 0.165 of the unshielded value.

## RADIOACTIVE DECAY EQUATION IN FULL

$$\frac{dN}{dt} = -\lambda N$$

$$\Rightarrow \frac{dN}{N} = -\lambda dt$$

$$\Rightarrow \int_{N_0}^{N_t} \frac{dN}{N} = -\int_0^t \lambda dt$$

$$\Rightarrow ln\left(\frac{N_t}{N_0}\right) = -\lambda t$$

$$\Rightarrow N_t = N_0 e^{-\lambda t}$$