Radioactivity

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Atomic Structure and Isotopes

- An atom is composed of a positively charged central nucleus inside a much larger cloud of negatively charged electrons.
- The mass of an atom is concentrated in the nucleus.
- Atomic nuclei are composed of two major particles, protons and neutrons.
- Protons are positively charged with a mass approximately 1850 times greater than that of an electron.
- The number of protons present in the nucleus is known as the atomic number (Z), and it determines what the element is, for example six protons in carbon.
- Neutrons are uncharged particles with a mass approximately equal to that of a proton.
- The sum of protons and neutrons in a given nucleus is the mass number (A). Thus:

  $A = Z + N$
- where N is the number of neutrons present.

Isotopes

- Atoms of a given element may not necessarily contain the same number of neutrons.
- Atoms of a given element with different mass numbers (i.e. different numbers of neutrons) are called isotopes.
- For example: ${}^{12}_{6}C$ ${}^{14}_{6}C$ ${}^{16}_{8}O$ ${}^{18}_{8}O$
- The number of isotopes of a given element varies: there are three isotopes of hydrogen (${}^{1}H$, ${}^{2}H$ and ${}^{3}H$), seven of carbon (${}^{10}C$ to ${}^{16}C$ inclusive).

Atomic stability and radiation

- In general, the ratio of neutrons to protons will determine whether an isotope of an element is stable enough to exist in nature.
- Stable isotopes for elements with low atomic numbers tend to have an equal number of neutrons and protons, whereas stability for elements of higher atomic numbers requires more neutrons.
- Unstable isotopes are called radioisotopes.
- They become stable isotopes by the process of radioactive decay: changes occur in the atomic nucleus, and particles and/or electromagnetic radiation are emitted.

Types of radioactive decay

- There are several types of radioactive decay; only those most relevant to biochemists are considered below.
- **Decay by negatron emission**
- In this case a neutron is converted to a proton by the ejection of a negatively charged beta (β) particle called a negatron (β^-):

$$\text{Neutron} \rightarrow \text{proton} + \text{negatron}$$

- To all intents and purposes a negatron is an electron, but the term negatron is preferred, although not always used, since it serves to emphasise the nuclear origin of the particle.
- As a result of negatron emission, the nucleus loses a neutron but gains a proton.
- The mass number, A, remains constant. An isotope frequently used in biological work that decays by negatron emission is ^{14}C.

$$^{14}_{6}\text{C} \rightarrow {}^{14}_{7}\text{N} + \beta^-$$

- Negatron emission is very important to biochemists because many of the commonly used radionuclides decay by this mechanism.
- Examples are: ^{3}H and ^{14}C, which can be used to label any organic compound; ^{35}S used to label methionine, for example to study protein synthesis; and ^{33}P or ^{32}P, powerful tools in molecular biology when used as nucleic acid labels.
- **Decay by positron emission**
- Some isotopes decay by emitting positively charged β particles referred to as positrons (β^{+}). This occurs when a proton is converted to a neutron:

$$\text{Proton} = \text{neutron} + \text{positron}$$

- Positrons are extremely unstable and have only a transient existence.

- Once they have dissipated their energy they interact with electrons and are annihilated.
- The mass and energy of the two particles are converted to two γ-rays emitted at 180° to each other.
- This phenomenon is frequently described as back-to-back emission.
- As a result of positron emission the nucleus loses a proton and gains a neutron, the mass number stays the same.
- An example of an isotope decaying by positron emission is ^{22}Na:

$$^{22}_{11}\mathrm{Na} \rightarrow {}^{22}_{10}\mathrm{Ne} + \beta^{+}$$

- Positron emitters are detected by the same instruments used to detect γ -radiation.
- They are used in biological sciences to spectacular effect in brain scanning with the technique positron emission tomography (PET scanning) used to identify active and inactive areas of the brain.

Decay by alpha particle emission

- Isotopes of elements with high atomic numbers frequently decay by emitting alpha (α) particles.
- An α -particle is a helium nucleus; it consists of two protons and two neutrons ($^{4}He^{2+}$).
- Emission of α -particles results in a considerable lightening of the nucleus, a decrease in atomic number of 2 and a decrease in the mass number of 4.
- Isotopes that decay by α -emission are not frequently encountered in biological work although they can be found in instruments such as scintillation counters and smoke alarms.
- Radium-226 (^{226}Ra) decays by α -emission to radon-222 (^{222}Rn), which is itself radioactive.
- Thus begins a complex decay series, which culminates in the formation of ^{206}Pb:

$$^{226}_{88}Ra \rightarrow {}^{4}_{2}He^{2+} + {}^{222}_{86}Rn \rightarrow\rightarrow\rightarrow {}^{206}_{82}Pb$$

- Alpha emitters are extremely toxic if ingested, due to the large mass and the ionising power of the a-particle.

Electron capture

- In this form of decay a proton captures an electron orbiting in the innermost K shell:

  proton + electron $\longrightarrow$ neutron + X-ray

- The proton becomes a neutron and electromagnetic radiation (X-rays) is given out.
- Example:

$$^{125}_{53}\mathrm{I} \rightarrow {}^{125}_{52}\mathrm{Te} + \text{X-ray}$$

Decay by emission of γ-rays

- In some cases α- and β-particle emission also give rise to γ-rays (electromagnetic radiation similar to, but with a shorter wavelength than, X-rays).
- The γ-radiation has low ionising power but high penetration. For example, the radiation from ^{60}Co will penetrate 15 cm of steel.
- The toxicity of γ -radiation is similar to that of X-rays.

Example:

$$^{131}_{53}\mathrm{I} \rightarrow {}^{131}_{54}\mathrm{Xe} + \beta^{-} + \gamma$$

Radioactive decay energy

- The usual unit used in expressing energy levels associated with radioactive decay is the electron volt.
- One electron volt (eV) is the energy acquired by one electron in accelerating through a potential difference of 1 V and is equivalent to 1.6×10^{-19} J.
- For the majority of isotopes, the term million or mega electron volts (MeV) is more applicable. Isotopes emitting α-particles are normally the most energetic, falling in the range 4.0 to 8.0 MeV, whereas β- and γ-emitters generally have decay energies of less than 3.0 MeV.
- The higher the energy of radiation the more it can penetrate matter and the more hazardous it becomes.

Rate of radioactive decay

- Radioactive decay (measured as disintegrations per minute, d.p.m.) is a spontaneous process and it occurs at a rate characteristic of the source, defined by the rate constant (λ, the fraction of an isotope decaying in unit time, t^{-1}).
- Decay is a nuclear event so λ is not affected by temperature or pressure.
- The number of atoms disintegrating at any time is proportional to the number of atoms of the isotope (N) present at that time (t).
- Clearly, the number of atoms N, is always falling (as atoms decay) and so the rate of decay (d.p.m.) falls with time.
- A graph of radioactivity against time shows a curve, called an exponential decay curve.
- The mathematical equation that underpins the graph shown is as follows:

$$\ln N_t / N_0 = -\lambda t$$

- where λ is the decay constant for an isotope, Nt is the number of radioactive atoms present at time t, and N_0 is the number of radioactive atoms orginally present.

… Rate of radioactive decay

- In practice it is more convenient to express the decay constant in terms of half-life ($t_{½}$).
- This is defined as the time taken for the activity to fall from any value to half that value.

$$\ln 1/2 = -\lambda t_{1/2}$$
$$\text{or } t_{1/2} = 0.693\lambda$$

Units of radioactivity

- The SI system uses the becquerel (Bq) as the unit of radioactivity.
- This is defined as one disintegration per second (1 d.p.s.).
- However, an older unit, not in the SI system and still frequently used, is the curie (Ci).
- This is defined as the quantity of radioactive material in which the number of nuclear disintegrations per second is the same as that in 1 g of radium, namely 3.7×10^{10} (or 37 GBq).
- For biological purposes this unit is too large and the microcurie (mCi) and millicurie (mCi) are used.
- It is important to realise that the units Bq and Ci refer to the number of disintegrations actually occurring in a sample not to the disintegrations detected, which generally will be only a proportion of the disintegrations occurring.
- Detected decays are referred to as counts (i.e. counts per second or c.p.s.).