Radioactivity

In the formation of molecules or ionic compounds, only the distribution of the electrons is affected. The nuclei of the atoms involved remain unchanged. However, in nuclear reactions, the composition of the nucleus will change, most often changing the identity of the element itself.

The two main processes we will discuss are radioactive decay, that is, the process in which a nucleus spontaneously disintegrates, giving off radiation, and nuclear bombardment reactions, where a nucleus is bombarded, or struck, by another nucleus or by a nuclear particle.

Antoine Henri Becquerel is credited with the discovery of radioactive phenomena. He first noticed that photographic plates could be exposed when placed in a box with certain uranium salts, and concluded that the minerals were radiating some type of energy.

The radiation from uranium can be separated (by passing it through an electromagnetic field generated by two oppositely charged plates) into three fundamental forms. The first are alpha particles, which are repelled by the positively charged plate indicating that they have a positive charge. We now understand that these alpha particles consist of two protons and two neutrons (essentially the same as a helium atom that has been stripped of its electrons). The nuclear symbol for the alpha particle includes its atomic number (the number of (+) charges it carries) and its mass number (the sum of its protons and neutrons).

\[
\text{The mass number} \quad 4 \alpha \text{ or } 4 \text{He}
\]

\[
\text{The atomic number} \quad 2 \\
\]

Beta particles bend the opposite direction as alpha particles when separated, indicating they have a negative charge. They resemble, at least in mass and charge, a very high speed electron that appears to be ejected by the nucleus of some unstable atoms. Since electrons do not reside in the nucleus, there are several theories as to how an "electron-like" particle could originate there. One plausible theory is that a neutron is actually a proton and electron "stuck" together. If the neutron were to eject its "electron" half, it would be converted into a proton. Since elements that undergo beta decay do increase in atomic number as they radiate, this is consistent with the theory.

Since beta particles are negatively charged, they are assigned an atomic number of -1 and a mass number of 0 (considering their mass to be 0.00055 amu, their mass is negligible compared to protons and neutrons). So, its symbol is

\[
\text{Beta particles} \quad -1 \beta \text{ or } -1 e
\]

Gamma rays are unaffected by electric charge; they have been demonstrated to be electromagnetic waves similar to x-rays, but of much shorter wavelength (and consequently, higher energy). Since gamma rays have no charge and, as light, have no rest mass, the symbol used for gamma rays is

\[
\text{Gamma rays} \quad 0 \gamma
\]
Nuclear Equations

Equations for nuclear reactions are similar to regular chemical reactions in that they are subject to a mass balance. In nuclear equations we use nuclide symbols to represent given isotopes of elements. The nuclide symbol includes the atomic number and the mass number of that particular isotope. In balancing a nuclear equation, one must simply ensure that the sum of atomic numbers and mass numbers on both sides of the arrow are equal.

For example, the alpha decay of Uranium-238 would be represented as

\[
\frac{238}{92}U \rightarrow \frac{234}{90}Th + \frac{4}{2}He
\]

In this example, Uranium is the "parent" nuclide, while thorium-234 is considered the "daughter" nuclide.

Reactant and product nuclei are always represented using nuclide symbols. Other particles that are involved in many nuclear equations are given the following symbols in which the subscript equals the charge and the superscript equals the mass number.

<table>
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<th>Particle</th>
<th>Symbol</th>
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<tr>
<td>Proton</td>
<td>$^1_1H$ or $^1_p$</td>
</tr>
<tr>
<td>Neutron</td>
<td>$^0_n$</td>
</tr>
<tr>
<td>Electron</td>
<td>$^0_{-1}e$ or $^0_{-1}\beta$</td>
</tr>
<tr>
<td>Positron</td>
<td>$^0_{+1}e$ or $^0_{+1}\beta$</td>
</tr>
<tr>
<td>Gamma photon</td>
<td>$^0 \gamma$</td>
</tr>
</tbody>
</table>

Beta emission of a nucleus involves the ejection of a beta particle from the nucleus. If you recall, this produces a daughter element with an atomic number one greater than the parent nuclide. For example, the equation for the beta decay of Technicium-99 produces Ruthenium-99 as its daughter.

\[
\frac{99}{43}Tc \rightarrow \frac{99}{44}Ru + \frac{0}{-1}e
\]

Note that in all nuclear equations, the total charge is conserved. This means that the sum of the subscripts on both sides of the arrow must tally. Likewise, the total mass is conserved requiring that the sum of the superscripts on both sides of the arrow must tally.

Positron emission involves the ejection of a positron from an unstable nucleus. A positron is similar to a beta particle, having the same mass but carrying a positive charge.

Gamma emission is simply the emission of a gamma photon, which carries no mass and no charge consequently has no effect on the parent nuclide’s atomic number or mass number. Gamma emission generally accompanies the emission of other radioactive particles, such as alpha or beta.
Nuclear Stability

One might wonder how you can manage to get so many positively charged protons to coexist in the nucleus, when like charges repel. Well, the current theory involves the nuclear force which is defined as a *strong force of attraction between nucleons that acts only at very short distances (about $10^{-15}$ m)*. Once we go beyond nuclear distances, these nuclear forces are negligible.

So, two protons that are farther apart than $10^{-15}$ m will repel one another. However, in the nucleus, where protons are in close proximity to one another, the nuclear force is quite effective, thereby giving a (sometimes) stable nucleus.

Circumstantial evidence points to the theory that protons and neutrons exist energy levels, much like electrons in an atom existing in discrete levels. The *shell model of the nucleus* is a nuclear model in which protons and neutrons exist in levels, or shells, analogous to the shell structure that exists for electrons in an atom.

In atoms, filled shells of electrons (such as, with the noble gases) are more stable. The total number of electrons for these stable atoms are 2 (for He), 10 (for Ne), 18 (for Ar), etc.. Similarly, it has been noted that nuclei with certain numbers of protons or neutrons appear to be unusually stable. These “stable” numbers (referred to as *magic* numbers) have been explained using the Shell model of the nucleus. According to this theory, a *magic number* is the *number of nuclear particles in a completed shell of protons or neutrons*. These numbers are **not the same** as for electrons.

**For protons, the magic numbers are 2, 8, 20, 28, 50, and 82.**

**For neutrons, the magic numbers are 2, 8, 20, 28, 50, 82, and 126.**

Evidence for these "magic numbers" can be seen in naturally occurring decay "series". Uranium-238 goes through a series of decays in which each daughter nuclide is unstable and continues to decay........until the final product, $^{206}_{82}$Pb. This nucleus is stable. It notably contains a magic number of protons. Other natural radioactive decay series end with $^{207}_{82}$Pb or $^{208}_{82}$Pb, each of which has a magic number of protons with $^{208}_{82}$Pb also having a magic number of neutrons.

There is also an indication that pairs of protons and neutrons will stabilize a nucleus (again analogous to the pairing of electrons in orbitals.) The table below indicates the number of stable isotopes of even vs odd protons/neutrons.

<table>
<thead>
<tr>
<th>Number of Stable Isotopes</th>
<th>157</th>
<th>52</th>
<th>50</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of neutrons</td>
<td>Even</td>
<td>Odd</td>
<td>Even</td>
<td>Odd</td>
</tr>
<tr>
<td>Number of protons</td>
<td>Even</td>
<td>Even</td>
<td>Odd</td>
<td>Odd</td>
</tr>
</tbody>
</table>

If we plot the number of neutrons (N) vs the number of protons (Z) for the known stable nuclides, we find that they fall in a certain region, forming a "**band of stability**". Refer to [Figure 1](#), depicting this band as you read the next section.
Types of Radioactive Decay

Listed below are five common types of radioactive decay.

**Alpha Emission** (abbreviated $\alpha$): emission of an alpha particle, or an $^{4}\text{He}$ nucleus, from an unstable nucleus.

For example, the alpha decay of Uranium-238 is written as

\[
^{238}_{92}\text{U} \longrightarrow ^{4}_{2}\text{He} + ^{234}_{90}\text{Th}
\]

The "daughter" nucleus has an atomic number two less than the "parent" and an atomic mass four less than the parent.

This type of decay is characteristic of elements with 84 or more protons. Alpha decay provides a decrease in the atomic number, and the daughter nuclide is more likely to be stable with 83 or less protons in its nucleus.

**Beta Emission** (abbreviated $\beta$ or $\beta^-$): emission of a high speed "nuclear" electron. This type of emission results in the conversion of a neutron into a proton,

\[
^{0}_{-1}\text{n} \longrightarrow ^{1}_{1}\text{p} + ^{0}_{-1}\beta
\]

thereby increasing the atomic number of the daughter element by one. Carbon-14 undergoes beta emission to become nitrogen-14.

\[
^{14}_{6}\text{C} \longrightarrow ^{14}_{7}\text{N} + ^{0}_{-1}\beta
\]

This type of decay is characteristic of atoms whose neutron to proton ratio, (N/Z), is too high to lie in the band of stability seen in Figure 1. Emission of a beta particle increases the number of protons and decreases the number of neutrons causing a decrease in the (N/Z) ratio, bringing the daughter nuclide closer to the stable band of ratios.

**Positron Emission** (abbreviated $\beta^+$): emission of a positron from an unstable nucleus. This type of emission results in the conversion of a proton into a neutron,

\[
^{1}_{1}\text{p} \longrightarrow ^{1}_{0}\text{n} + ^{0}_{+1}\beta
\]

thereby, decreasing the atomic number by one. This type of decay is characteristic of elements whose neutron to proton ratio (N/Z) is too low and lie to the right of the band of stability seen in Figure 1. By emitting a positron, the (N/Z) ratio increases, and the daughter nucleus will now lie closer to the stable band.

For example, the positron decay of Bismuth-208.

\[
^{208}_{83}\text{Bi} \longrightarrow ^{208}_{82}\text{Pb} + ^{0}_{+1}\beta
\]
**Electron Capture** (abbreviated EC): the decay of an unstable nucleus by absorbing an electron from an inner orbital of an atom. As in positron emission, the effect is to change a proton into a neutron.

\[
^1_1\text{P} + ^0_{-1}\text{e} \rightarrow ^1_0\text{n}
\]

For example, the EC decay of Potassium-40.

\[
^40_{19}\text{K} + ^0_{-1}\text{e} \rightarrow ^40_{18}\text{Ar}
\]

Note that the daughter element has an atomic number 1 less than the parent. This type of decay is characteristic of those isotopes where the N/Z ratio is too low.

When an electron from another orbital falls to fill the vacancy created by the captured electron, **an x-ray photon is emitted**. Potassium-40 can also undergo beta and positron decay.

**Gamma emission** (abbreviated g): Emission of a gamma photon from an excited nucleus with a wavelength in the area of 10-12 m.

In general, the radioactive decay of a nuclide results in a "excited" product nuclei. This excited daughter nuclide will return immediately to its ground state by emitting electromagnetic radiation (generally in the gamma region of the spectrum).

Although this emission usually happens immediately, some nuclides exist for a short time (10-9 sec) in a metastable state before they emit a gamma photon. A metastable nucleus is one in an exited state with a lifetime of at least 1 nanosecond. The following is an example of how this decay is depicted in equation form. Technecium-99, used in medical diagnosis, is an example of an exited nucleus with a significant lifetime.

\[
^99_{43}\text{Tc} \rightarrow ^99_{43}\text{Tc} + ^0_{0}\gamma
\]

In summary, the prediction of the type of decay a nuclide may undergo is supported by Figure 1.

*Those nuclides with atomic numbers greater than 83 will likely undergo alpha decay.*

*Those nuclides to the left of the stability band (N/Z ratio too high) will likely undergo beta emission.*

*Those nuclides to the right of the stability band (N/Z ratio too low) will likely undergo positron emission or electron capture.*
Radioactive Decay Series

As mentioned earlier, all nuclides with atomic numbers greater than 83 are radioactive. In some cases, where a radioactive nucleus is very large, the daughter element of its decay will likely be unstable and continue to emit. This results in a sequence of decays until a stable nucleus is reached, which is usually a stable isotope of lead.

There are only three naturally occurring radioactive decay series. Uranium-238 and uranium-235 both undergo a series of decays that eventually produce lead-206 and lead-207, respectively.

Thorium-232 also undergoes a natural series of decays to eventually yield lead-208.

Nuclear Bombardment Reactions.

So far, we have only looked at spontaneous radioactive decays. It is possible, however, to initiate the change of a nucleus, transmutation, by striking it with other nuclei or nuclear particles, such as protons or neutrons.

In 1919, Ernest Rutherford used a radioactive source of alpha particles to bombard nitrogen-7 nuclei. The result below not only provided evidence for the existence of protons, but also showed that one element could be transmuted into another.

\[
\begin{align*}
{^7_4}N + {^2_4}He & \rightarrow {^8_8}O + {^1_1}p \\
\end{align*}
\]

Since then, bombardment reactions have led to the discovery of the neutron (in 1932 by James Chadwick), the production of new radioactive isotopes, and most currently, the study of "subnuclear" particles.

In order to carry out bombardment reactions on large nuclei requires very high speeds for incoming particles. This required the development of "accelerator" technology. A particle accelerator is a device used to accelerate electrons, protons, and alpha particles and other ions to very high speeds.

Generally, the kinetic energy of these particles is measured in electron-volts. An electron-volt (eV) is the quantity of energy required to accelerate an electron by one volt potential difference. The equivalent, in Joules, is \(1.602 \times 10^{-19}\) J.

\[
1\ eV = 1.602 \times 10^{-19}\ J
\]

Typically, accelerators provide millions of electron-volts to these charged "bullets".
Detection and Biological Effects

Because radioactive particles can ionize molecules and cleave covalent bonds, they can adversely effect biological systems.

The detection and measurement of radiation is done by two fundamental methods. First, ionization counters, such as the Geiger counter, detect the production of ions in matter. The Geiger counter uses a probe filled with argon gas. As ionizing radioactive particles enter the probe, argon ions are formed and detected electrically.

Scintillation counters, on the other hand, measure light flashes emitted by a "phosphor" when struck with radioactive particles. (A phosphor is a substance that emits light when struck with nuclear particles.)

A radiation counter basically measures the number of disintegrations/second in a radioactive sample. This is referred to as the "Activity" of a sample. The unit used for activity is the "Curie". It was based on the activity of 1.00 gram of radium-226 which decays at a rate of 3.7 x 1010 disintegrations/s. So,

\[
1 \text{ Curie (Ci)} = 3.7 \times 10^{10} \text{ disintegrations/sec}
\]

Biological Effects and Dosage

The measure of the actual energy imparted when an object is exposed to a source of radiation is the rad (radiation absorbed dose). The rad is defined as the amount of radiation that delivers \(1 \times 10^{-2}\) J of energy per kilogram of tissue.

But the actual biological effect of radiation not only depends on the energy involved, but also on the type of radiation. For example, the same number of rads of neutron exposure is more damaging than a rad equivalent of gamma radiation. If we use a factor to represent the relative biological effect (RBE), which varies from particle to particle, and incorporate this, we get the rem (radiation equivalent in humans).

\[
\text{rems} = \text{rads} \times \text{RBE}
\]

Safe limits of radiation will always be debated. Detectable effects can be noticed with exposures as low as 30 rems. A single dose of 500 rems is generally fatal. It is generally accepted that exposure time is critical to the measurement of damage. Several small doses are less damaging than a single large dose.

Humans are subjected to about 0.1 rem per year from background radiation originating from the earth's crust or space. Other small exposures, such as dental x-rays, contribute about the same amount as background radiation.
Rate of Radioactive Decay

Radioactive decays are first-order by nature. Their rate of decay (the number of disintegrations per second) depends only on the number of radioactive nuclei that are left at any time "t". The Rate Law for any decay would be

\[
\text{Rate} = k N_t
\]

where \( N_t \) is the number of radioactive nuclei at time \( t \) and \( k \) is the decay constant particular to that radioactive nuclide.

If you recall from our discussion of first-order reactions in Chapter 13, the half-life of a first-order reaction is constant and independent of the original concentration of the sample. We related (in Ch.13) the half-life, \( t_{1/2} \), with the rate constant, \( k \) (in this case, the decay constant) by the following expression.

\[
t_{\frac{1}{2}} = \frac{0.693}{k}
\]

So, the decay constant for a given nuclide will give you its half-life. Since tables of half-lives are common, you can also obtain the decay constant given the half-life of a nuclide.

In order to calculate the fraction of the radioactive nuclei that remain after a given period of time, we must revisit our concentration-time equation for first-order reactions.

\[
\log \frac{N_t}{N_o} = -\frac{kt}{2.303}
\]

Here, \( N_t \) is the number of nuclei left after time, \( t \) and \( N_o \) is the number of nuclei initially.
Energy of Nuclear Reactions

The change in energy that occurs during a nuclear reaction is related to a change in mass according to the mass-energy equivalence relation derived by Albert Einstein in 1905.

\[ E = mc^2 \]

where energy is in joules, \( m \) is the mass in kg, and \( c \) is the speed of light \( (3.00 \times 10^8 \text{ m/s}) \).

From a table of nuclear masses you can use Einstein's equation to calculate the energy change for a nuclear reaction.

This equivalence of mass and energy does support the fact that the mass of a nucleus is always less than the sum of its constituent nucleons. (at least for stable nuclei)

The binding energy of a nucleus is the energy required to break it apart into its individual protons and neutrons.

The mass defect of a nucleus is the total mass of its nucleons minus the mass of the nucleus itself.
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