19.2: Naturally Occurring Radioactivity

When we discuss natural radioactivity in the sections under The Structure of Atoms, we mention the properties of α particles, β particles, and γ rays, but little attention is paid to the atoms which are left behind when one of these forms of radiation is emitted. Now we consider the subject of radioactivity in more detail.

α Emission

An alpha particle corresponds to a helium nucleus. It consists of two protons and two neutrons, and so it has a mass number of 4 and an atomic number (nuclear charge) of 2. From a chemical point of view we would write it as He^{2+}, indicating its lack of two electrons with the superscript 2+. In writing a nuclear reaction, though, it is unnecessary to specify the charge, because the presence or absence of electrons around the nucleus is usually unimportant. For these purposes an α particle is indicated as ${}^{4}_{2}\mathrm{He}$ or ${}^{4}_{2}\alpha$.

In certain nuclei a particles are produced by combination of two protons and two neutrons which are then emitted. An example of naturally occurring emission of an α particle is the disintegration of one of the isotopes of uranium, ${}^{238}_{92}\mathrm{U}$. The equation for this process is

$$ {}^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He} \tag{19.2.1}$$

Note that if we sum the mass numbers on each side of a **nuclear equation**, such as Equation 19.2.1, the total is the same. That is, 238 on the left equals 234 + 4 on the right. Similarly, the atomic numbers (subscripts) must also balance (92 on the left and 90 + 2 on the right). This is a general rule which must be followed in writing any nuclear reaction. The total number of nucleons (i.e., protons and neutrons) remains unchanged, and electrical charge is neither created nor destroyed in the process.

When a nucleus emits an a particle, its atomic number is reduced by 2 and it becomes the nucleus of an element two places earlier in the periodic table. That one element could transmute into another in this fashion was first demonstrated by Rutherford and Soddy in 1902. It caused a tremendous stir in the scientific circles of the day since it quite clearly contradicted Dalton's hypothesis that atoms are immutable. It gave Rutherford, who was then working at McGill University in Canada, an international reputation.

The type of nucleus that will spontaneously emit an a particle is fairly restricted. The mass number is usually greater than 209 and the atomic number greater than 82. In addition the nucleus must have a lower ratio of neutrons to protons than normal. The emission of an a particle raises the neutron/proton ratio as illustrated by the nuclear equation

$$ {}^{210}_{84}\mathrm{Po} \rightarrow {}^{206}_{82}\mathrm{Pb} + {}^{4}_{2}\mathrm{He} $$

The nucleus of ${}^{210}_{84}\mathrm{Po}$ contains 210 – 84 = 126 neutrons and 84 protons, giving a ratio of 126:84 = 1.500. This is increased to 124:82 = 1.512 by the α-emission.

β Emission

A beta particle is an electron which has been emitted from an atomic nucleus. It has a very small mass and is therefore assigned a mass number of 0. The β particle has a negative electrical charge, and so its nuclear charge is taken to be –1. Thus it is given the symbol ${}^{0}_{-1}e$ or ${}^{0}_{-1}\beta$ in a nuclear equation. Two examples of unstable nuclei which emit β particles are

$$ {}^{234}_{90}\mathrm{Th} \longrightarrow {}^{234}_{91}\mathrm{Pa} + {}^{0}_{-1}\mathrm{e} $$

and

$$ {}^{14}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} + {}^{0}_{-1}e $$

Note that both of these equations accord with the conservation of mass number and atomic number, showing again that both the total number of nucleons and the total electrical charge remain unchanged. We can consider a β particle emitted from a nucleus to result from the transformation of a neutron into a proton and an electron according to the reaction

$$ {}^{1}_{0}n \rightarrow {}^{1}_{1}p + {}^{0}_{-1}e $$

(Indeed, free neutrons unattached to any nucleus soon decay in this way.) Thus when a nucleus emits a β particle, the nuclear charge rises by 1 while the mass number is unaltered. Therefore the disintegration of a nucleus by β decay produces the nucleus of an element one place *further along* in the periodic table than the original element.

β decay is a very common form of radioactive disintegration and, unlike α decay, is found among both heavy and light nuclei. Nuclei which disintegrate in this way usually have a neutron/proton ratio which is higher than normal. When a β particle is lost, a neutron is replaced by a proton and the neutron/proton ratio decreases. For example, in the decay process

$$^{206}_{82}\text{Pb} \rightarrow\, ^{206}_{83}\text{Bi} + \,^{0}_{-1}e$$

the neutron/proton ratio changes from 1.561 to 1.530.

γ Radiation

Gamma rays correspond to electromagnetic radiation similar to light waves or radiowaves except that they have an extremely short wavelength—about a picometer. Because of the wave-particle duality we can also think of them as particles or photons having the same velocity as light and an extremely high energy. Since they have zero charge and are not nucleons, they are denoted in nuclear equations by the symbol $^0_0\gamma$ or, more simply, γ.

Virtually all nuclear reactions are accompanied by the emission of γ rays. This is because the occurrence of a nuclear transformation usually leaves the resultant nucleus in an unstable high-energy state. The nucleus then loses energy in the form of a γ-ray photon as it adopts a lower-energy more stable form. Usually these two processes succeed each other so rapidly that they cannot be distinguished. Thus when ^{238}U decays by α emission, it also emits a γ ray. This is actually a two-stage process. In the first stage a high-energy (or excited) form of ^{234}Th is produced:

$$^{238}_{92}\text{U} \rightarrow\, ^{234}_{90}\text{Th}^{*} + \,^{4}_{2}\text{He} \tag{19.2.2}$$

This excited nucleus-then emits a γ ray:

$$^{234}_{90}\text{Th}^{*} \rightarrow\, ^{234}_{90}\text{Th} + \,^{0}_{0}\gamma \tag{19.2.3}$$

Usually when a nuclear reaction is written, the γ ray is omitted. Thus Equations 19.2.2 and 19.2.3 are usually combined to give

$$^{238}_{92}\text{U} \rightarrow\, ^{234}_{90}\text{Th} + \,^{4}_{2}\text{He}$$