19.3: Radioactive Series

Naturally occurring uranium contains more than 99% $^{238}_{92}\text{U}$ that decays to $^{234}_{90}\text{Th}$ by α emission:

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

The product of this reaction is also radioactive, however, and undergoes β decay:

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

The $^{234}_{91}\text{Pa}$ produced in this second reaction also emits a β particle:

$$^{234}_{91}\text{Pa} \longrightarrow {}^{234}_{92}\text{U} + {}^{0}_{-1}\text{e}$$

These three reactions are only the first of 14 steps. After emission of eight α particles and six β particles, the isotope $^{206}_{82}\text{Pb}$ is produced. It has a stable nucleus which does not disintegrate further. The complete process may be written as follows:

$^{238}_{92}\text{U} \xrightarrow{\alpha} {}^{234}_{90}\text{Th} \xrightarrow{\beta} {}^{234}_{91}\text{Pa} \xrightarrow{\beta} {}^{234}_{92}\text{U} \xrightarrow{\alpha} {}^{230}_{90}\text{Th} \xrightarrow{\alpha} {}^{226}_{88}\text{Ra} \xrightarrow{\alpha} {}^{222}_{88}\text{Rn}$

$\downarrow^{\alpha}$ (2a)

$^{206}_{82}\text{Pb} \xleftarrow{\alpha} {}^{210}_{84}\text{Po} \xleftarrow{\beta} {}^{210}_{83}\text{Bi} \xleftarrow{\alpha} {}^{210}_{82}\text{Pb} \xleftarrow{\alpha} {}^{214}_{84}\text{Po} \xleftarrow{\beta} {}^{214}_{83}\text{Bi} \xleftarrow{\beta} {}^{214}_{82}\text{Pb} \xleftarrow{\alpha} {}^{218}_{84}\text{Po}$

While the net reaction is

$$^{238}_{92}\text{U} \rightarrow {}^{206}_{82}\text{Pb} + 8{}^{4}_{2}\text{He} + 6{}^{0}_{-1}e$$

Such a series of successive nuclear reactions is called a **radioactive series**. Two other radioactive series similar to the one just described occur in nature. One of these starts with the isotope $^{232}_{90}\text{Th}$ and involves 10 successive stages, while the other starts with $^{235}_{92}\text{U}$ and involves 11 stages. Each of the three series produces a different stable isotope of lead.

Example 19.3.1: Uranium-Actinium Series

The first four stages in the uranium-actinium series involve the emission of an α particle from a $^{235}_{92}\text{U}$ nucleus, followed successively by the emission of a β particle, a second α particle, and then a second β particle. Write out equations to describe all four nuclear reactions.

Solution

The emission of an a particle lowers the atomic number by 2 (from 92 to 90). Since element 90 is thorium, we have

$$^{235}_{92}\text{U} \longrightarrow {}^{231}_{90}\text{Th} + {}^{4}_{2}\text{He}$$

The emission of a β particle now increases the atomic number by 1 to give an isotope of element 91, protactinium:

$$^{231}_{90}\text{Th} \longrightarrow {}^{231}_{91}\text{Pa} + {}^{0}_{-1}\text{e}$$

The next two stages follow similarly:

$$^{231}_{91}\text{Pa} \longrightarrow {}^{227}_{89}\text{Ac} + {}^{4}_{2}\text{He}$$

and

$$^{227}_{89}\text{Ac} \longrightarrow {}^{227}_{90}\text{Th} + {}^{0}_{-1}\text{e}$$

Example 19.3.2: Thorium Series

In the thorium series, $^{232}_{90}\text{Th}$ loses a total of six α particles and four β particles in a 10-stage process. What isotope is finally produced in this series?

Solution

The loss of six α particles and four β particles:

$$6\,{}^{4}_{2}\mathrm{He} + 4\,{}^{\;0}_{-1}\mathrm{e}$$

involves the total loss of 24 nucleons and 6 × 2 – 4 = 8 positive charges from the ${}^{232}_{90}\mathrm{Th}$ nucleus. The eventual result will be an isotope of mass number 232 – 24 = 208 and a nuclear charge of 90 – 8 = 82. Since element 82 is Pb, we can write

$${}^{232}_{90}\mathrm{Th} \longrightarrow {}^{208}_{82}\mathrm{Pb} + 6\,{}^{4}_{2}\mathrm{He} + 4\,{}^{\;0}_{-1}\mathrm{e}$$