16.4: Radioactivity

Nuclear decay or *radioactive decay* is the process by which atoms of a certain element spontaneously transform into atoms of a different element, while radiating (emitting) energy. This spontaneous decay process occurs for atoms with more than 82 protons. The concept of the BEN and the BEN curve help us to understand that when massive atoms split apart, the result is more stable atoms. Einstein's mass-energy relationship lets us calculate how much energy is released during this process. We can do all this without knowing why any of it happens; we're just collecting and analyzing data.

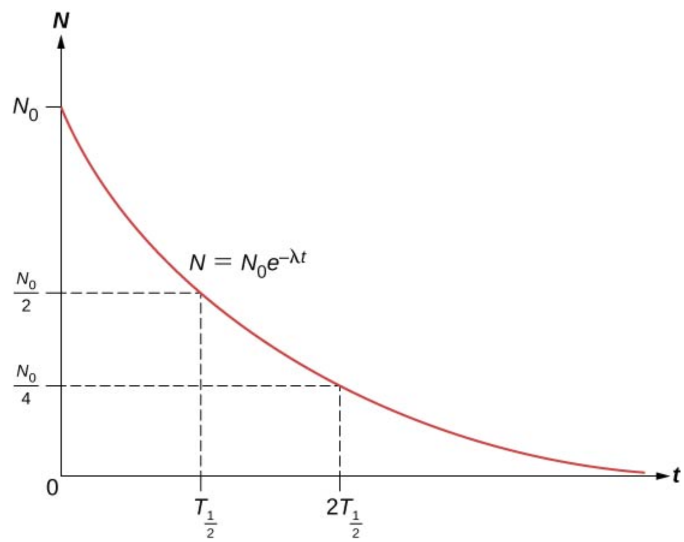
Experimental data shows that different elements decay at different rates and so we say that each radioactive element has a different *decay constant*. We use the Greek letter lambda (λ) to represent this value. By statistical analysis of the data it is possible to determine the *Radioactive Decay Law*:

$$N = N_0e^{-\lambda t}$$

This equation tells us that if you start with some number of atoms (N_0), then after some time (t), you will have N atoms left. The rest will have transformed into a different element. After some amount of time, you will half one-half of the original number of atoms that you started with. We call that amount of time the *half-life*. By setting $N = 1/2(N_0)$ and solving the decay equation you obtain a relationship between the decay constant and the half-life.

$$T_{1/2} = (0.693)/\lambda$$

Below is a graph of the number of atoms remaining in the sample as a function of time. You can see that the number of atoms decreases quickly, and that after each period of time equal to one half-life, the number of atoms remaining has decreased by a factor of two.



Radioactive Decay Curve taken from OpenStax *University Physics vol. 3* and is licensed under CC-BY

Example 16.4.1

There are 10,000 atoms of a particular type. How many remain after five half-lives?

Solution

After one half-life, there are 5000 atoms remaining. After two, there are 2500. After three, 1250. Four half-lives leaves 625 and five gives 312.5 atoms remaining. Of course, you can't have a half-atom. An atom has either transformed, or it hasn't. So, after five half-lives, you would have either 312 or 313 atoms remaining.

How many atoms transform each second is called the *activity* of the element. High activities are paired with short half-lives and large decay constants. Atoms that are very stable have low activities, long half-lives and small decay constants. The activity may be determined from the decay law:

$$\text{Activity} = \lambda N = \lambda N_0 e^{-\lambda t}$$

Although the decay law is valid for a sample with a large number of atoms in it, there is no way to tell which atom will decay at any given time. At best, statistics can be used to identify the average amount of time an atom exists before decaying. We call this the *mean lifetime* of an atom, often just called the lifetime.

$$T_{\text{lifetime}} = 1/\lambda$$

Example 16.4.2

The half-life of strontium-90 is 28.8 years. Determine the decay constant and the activity of a 1.50 gram sample of the material.

Solution

The decay constant is found by the half-life, which should be converted into seconds:

$\lambda = \frac{0.693}{9.101 \times 10^8 \text{seconds}} = 7.61 \times 10^{-10}\ \text{s}^{-1}$

To determine the activity, the number of atoms in the sample must be determined. Strontium-90 has a molar mass of 87.62 grams per mol. Therefore $1.50 \text{ grams} \times \frac{1 \text{mol}}{87.62 \text{ grams}} \times \frac{6.02 \times 10^{23} \text{atoms}}{1 \text{ mol}} = 1.0309 \times 10^{22} \text{ atoms}$

$A_0 = 7.61 \times 10^{-10}\ \text{s}^{-1} \times 1.0309 \times 10^{22} \text{ atoms} = 7.845 \times 10^{12}\ \frac{\text{decays}}{\text{second}}$

Radioactive Dating

Understanding the decay rates of different atoms is the basis for *radioactive dating*. Probably the most familiar example of this is carbon-14 dating. Carbon-14 is a naturally occurring isotope of carbon. That means it behaves like carbon-12, so it is part of every living organism. As long as the organism is living, it takes in carbon and a fraction of this is carbon-14. However, carbon-14 decays over time with a half-life of 5730 years. By comparing the current amount of carbon-14 in an organism to the expected amount, it is possible to determine how much time has passed since the organism died. Because carbon-14 has a fairly short half-life, this technique has a limit of about 50,000 years. Items older than this will have practically no carbon-14 left in them and so different elements must be used. Uranium-238 has a half-life of more than four billion years, allowing for determining age on a much longer time scale.

Types of Radioactive Decay

Regardless of the lifetime, the data has shown that there are only a small number of ways that atoms can decay. Initially, there is a 'parent nucleus' that decays into multiple 'daughter nuclei'. The process can be written as a type of equation that describes how the decay takes place. The parent is on the left, and an arrow points towards the daughters.

The first type of decay that was measured is called *alpha decay*. In this decay mode, the parent nucleus splits into a daughter and a helium nucleus. The Helium nucleus consists of two neutrons and two protons and is often called an *alpha particle*.

For alpha decay, the process can be written symbolically as:

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

In *beta decay* processes the parent transforms into a daughter and two other particles. There are actually two types of beta decays. In the first type, the parent becomes a daughter, an electron and a third particle called an electron antineutrino. In the second process, the parent becomes a daughter, a positron and an electron neutrino.

One of the stranger things that comes from the study of nuclear physics is the concept of the *antiparticle*. Antiparticles have the same mass as the 'normal' version, but if the particle has a net charge, the antiparticle will have the same amount of charge but the opposite sign of charge. An antielectron (also called a positron) is a particle that has the same amount of mass and charge as an electron, but the charge is positive. The electron antineutrino is the antiparticle to the electron neutrino. Neutrinos and antineutrinos are particles that have no charge and incredibly small masses.

Beta decay is the result of a nucleon in the parent nucleus transforming from one type to another. For example, a neutron can decay into a proton, electron and an electron antineutrino.

$$ {}^{A}_{Z}\mathrm{X} \rightarrow {}^{A}_{Z+1}\mathrm{Y} + {}^{0}_{-1}\mathrm{e} + {}^{0}_{0}\bar{\nu}_e $$

You can see that the nucleon number is the same, and the increase in the positive charge is offset by by the appearance of the electron. It is also possible for a proton to transform into a neutron, a positron and an electron neutrino:

$$ {}^{A}_{Z}\mathrm{X} \rightarrow {}^{A}_{Z-1}\mathrm{Y} + {}^{0}_{+1}\mathrm{e} + {}^{0}_{0}\,\nu_e $$

It is important to understand that the daughter particles are created during the decay process by mass-energy conversion. They do not exist before the decay. This is analogous to the behavior of atomic electrons. When an electron moves from an outer orbital to one closer to the nucleus, the electron moves to a lower energy state and so the atom has to lose energy. The way the atom loses energy is to emit a photon. The photon didn't exist before the electron transition, it was produced by the electron transition.

Similarly, when the neutron decays into a proton, an electron, and an antineutrino, only the neutron existed before the decay. The other three particles are created by the decay. Although perhaps counterintuitive, this is consistent with Einstein's mass-energy relationship.

There is one final way that a nucleus can lose energy. This process is completely analagous to the way an excited atom loses energy. The excited nucleus sheds energy by emitting a very high energy photon. This process is called *gamma decay*. In this process the nucleus does not transform into another element. The asterisk (*) is used to denote the excited nucleus.

$$ {}^{A}_{Z}\mathrm{X}^{*} \rightarrow {}^{A}_{Z}\mathrm{X} + \gamma $$

Why exactly would a neutron suddenly transform into a proton, or vice versa? The question is obvious, and an obvious answer is that decay tends to increase the stability of the system. How that is understood requires that we enter the world of subatomic particle physics and quarks. Those topics are generally beyond the scope of this text, but the general idea is that neither protons nor neutrons are fundamental particles.

In much the same way that a nucleus can be treated as a single object or as a collection of nucleons, a nucleon can be thought of in the same way. On one level, a nucleon is a single object. On another scale, a nucleon is a collection of objects called quarks. Quarks have properties like mass and charge, but they also have properties that are less familiar. Quarks are also described in terms of charm and strangeness. Quark-quark interactions follow certain rules that physicists have been trying to decipher since the first evidence of quarks was detected in 1968.

Radioactive Decay Series

Radioactive parent elements will spontaneously split to raise the daughter's BEN and make the daughters more stable than the parent. It is quite likely that the daughters can also become more stable by decaying. The daughters from the first decay become the parent for the second decay, and so on. The decay series will end when the BEN of the final stage is near the maximum possible. Whether the decay happens by alpha, beta or gamma decay depends on many different factors that are beyond the scope of this text. An example involving Thorium decaying into Lead is shown below.

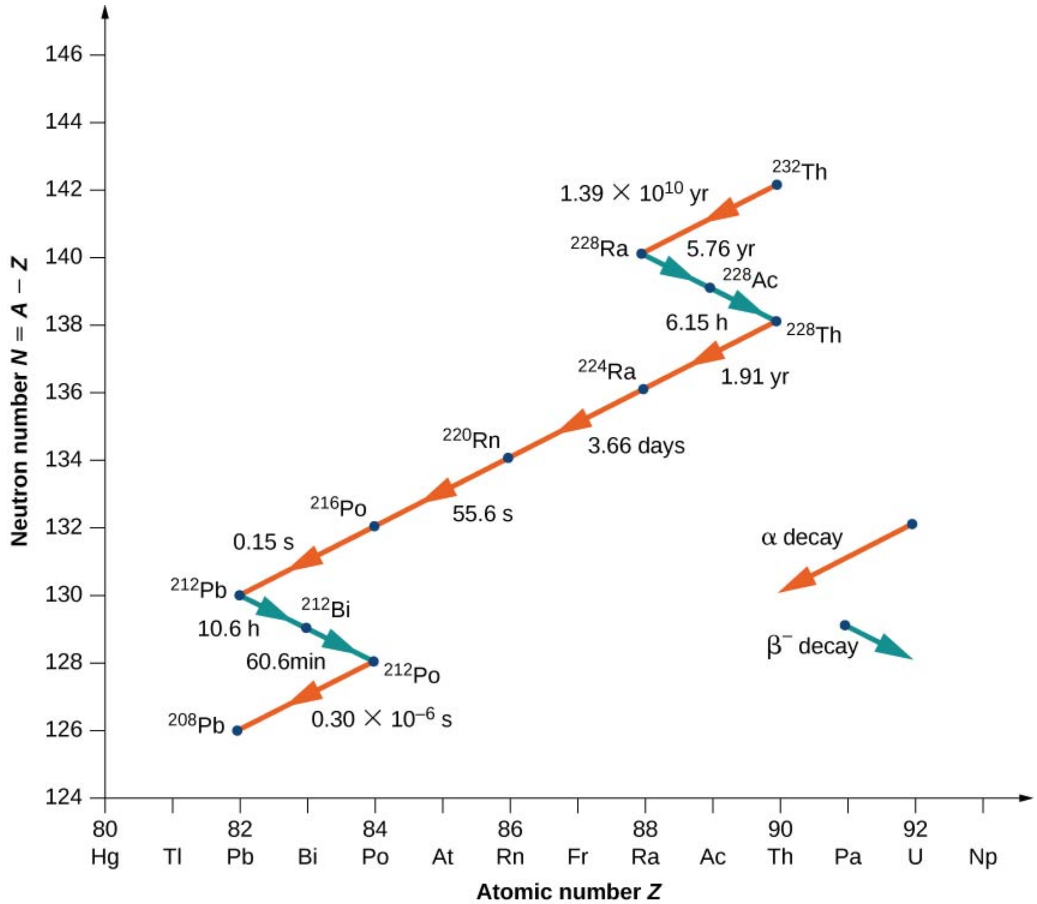
$$ {}^{232}_{90}\mathrm{Th} \rightarrow {}^{228}_{88}\mathrm{Ra} + {}^{4}_{2}\alpha $$

$$ {}^{228}_{88}\mathrm{Ra} \rightarrow {}^{228}_{89}\mathrm{Ac} + {}^{0}_{-1}\mathrm{e} + {}^{0}_{0}\bar{\nu}_e $$

$$ {}^{228}_{89}\mathrm{Ac} \rightarrow {}^{228}_{90}\mathrm{Th} + {}^{0}_{-1}\mathrm{e} + {}^{0}_{0}\bar{\nu}_e $$

$$ {}^{228}_{90}\mathrm{Th} \rightarrow {}^{224}_{86}\mathrm{Ra} + {}^{4}_{2}\alpha $$

After a series of alpha and beta decays the Thorium atoms become stable isotopes of Lead. The half-lives for each of the decays is shown on the graph. Some portions of the decay series occur over very long times and others take only fractions of a second, according to the decay constant for each element.



Thorium Decay Chain taken from OpenStax *University Physics vol. 3* and is licensed under CC-BY

The energy released to the environment by the radioactive decay of atoms includes the kinetic energy of the daughters and other particles created by the decay, and the energy of any photons emitted. The release of energy by radioactive decay helps geologists understand why the earth's core is hotter than expected. This energy transfer forms the basis for the nuclear power plant and also appears in medicine as both the cause of, and cure for, certain cancers.
