Natural Radioactivity

Natural radioactivity is the activity existing in nature. Spontaneous emission of particles or electromagnetic radiation, or both from an unstable nucleus is labeled as radioactivity. There are three kinds of radiation; α-particle (alpha-particle), β-particles(beta-particle) and γ-rays (gamma-rays) or γ-radiation.

α-particles are the nuclei of helium atoms with charge 2 and mass 4 ($^{4}_{2}He$) , which are massive than any other particle that prevents them to travel to a greater distance. They cannot penetrate the skin under small exposure. However, a sever skin burn may results by enough exposure.

β-particles are the particles with charge -1 and mass zero ($^{0}_{-1}e$). They are extremely small and can travel farther than alpha-particles and have the ability to penetrate the skin.

γ-rays (radiation) consist of high energy photons ($^{0}_{0}\gamma$). Since they are not the particles, they have extremely penetrating power that can only blocked by highly dense material like lead (Pb).

The disintegration of a radioactive nucleus is conveniently represented in the form of **radioactive decay series** that consists of a sequence of nuclear reactions that ultimately ends in a stable isotope. Some of these are the uranium series, the thorium series, and the neptunium series. For example, the principle isotope of uranium is ^{238}U that constitutes 99.3% of the natural element and has the half-life of 4.5 x 10^9 years. It disintegrates by emitting an alpha-particle forming ^{234}Th. This isotope undergoes a beta-emission forming ^{234}Pa, which in turn disintegrates into ^{234}U. Then five successive emissions occur giving ^{214}Pb, which ultimately ends in ^{206}Pb, a stable isotope. This involves fourteen steps. You may consult any standard general chemistry textbook for further information.

Dating Based on Radioactive Decay

The most interesting application of natural radioactivity is the determination of the age of ancient objects. The type of dating involves the nature of old objects; carbon dating is suitable for objects containing carbon, such as, bone, teeth, cloth, etc., uranium-238 (^{238}U) dating is most commonly applied to determine the age of rocks in the earth and extraterrestrial objects, and potassium-40 (^{40}K) dating is good for minerals and rocks.

Incidentally, the technique of radiocarbon dating was developed by an American physical chemist, Willard F. Libby:

Willard F. Libby

The Nobel Prize in Chemistry 1960
(taken from http://nobelprize.org/nobel_prizes/chemistry/laureates/1960/libby-bio.html)

Radiocarbon Dating

This technique is based on the radiocarbon, ^{14}C, which is produced when atmospheric nitrogen is bombarded by cosmic rays(neutrons) ejecting proton as follows:

$$^{14}_{7}N + ^{1}_{0}n \longrightarrow ^{14}_{6}C + ^{1}_{1}H$$

Further, the radioactive C-14 isotope, which has the half-life of 5730 years, decays by emitting the beta-particle with the formation of $^{14}{}_{7}N$:

$$^{14}_{6}C \longrightarrow ^{14}_{7}N + ^{0}_{-1}\beta \qquad \text{half-life = 5730 years}$$

This C-14 enters the biosphere as CO_2, which is absorbed by plants during the photosynthesis in addition to normal C-12. Plant- eating mammals exhale both normal C-12 and C-14 in CO_2. Eventually, a dynamic equilibrium establishes between the living tissues and the atmosphere where C-14 to C-12 ratio remains constant. But when a living tissue dies, the C-14 is no longer replenished resulting in the decrease C-14 to C-12 ratio due to decay of C-14. Decrease in this ratio can be exploited to determine the age of ancient objects. How do we do that?

The radioactive decay process obeys the first-order kinetics that is given by

$$\ln \frac{N_0}{N_t} = k\,t$$

where N_0 and N_t are the number of C-14 nuclei at time t =0 (present) and t=t (past), and k is first-order rate constant that is related to half-life through the following equation.

$$t_{1/2} = \frac{0.693}{k}$$

The k for C-14 is

$$k = \frac{0.693}{5730\,years} = 1.21x10^{-4}\ year^{-1}$$

Thus the age can be calculated by rearranging the fist equation and substituting the last equation for k:

$$t = \frac{1}{k}\ln\frac{N_0}{N_t} = \frac{1}{1.21x10^{-4}\ year^{-1}}\ln\frac{decay\,rate\,of\ fresh\,sample}{decay\,rate\,of\ old\ sample}$$

Therefore, by measuring the decay rates of the old sample and compatible new sample, one can calculate t, the age of an old object in years.

Example (from General Chemistry – Raymond Chang)

The C-14 decay rate of a sample obtained from a fresh tree is 0.260 disintegrations per second per gram of sample. Another wood sample prepared from an old object recovered at an archeological excavation gives a decay rate of 0.186 disintegrations per second per gram. What is the age of the old object?

Answer

Here

The decay rate of fresh sample = 0.260
The decay rate of old sample = 0.186

Then

$$t = \frac{1}{1.21x10^{-4}\ year^{-1}} \ln \frac{decay\ rate\ of\ fresh\ sample}{decay\ rate\ of\ old\ sample}$$

$$t = \frac{1}{1.21x10^{-4}\ year^{-1}} \ln \frac{0.260}{0.186} = 2768\ years$$

The following is a great link for radiocarbon dating applications and literature

http://www.c14dating.com/applic.html