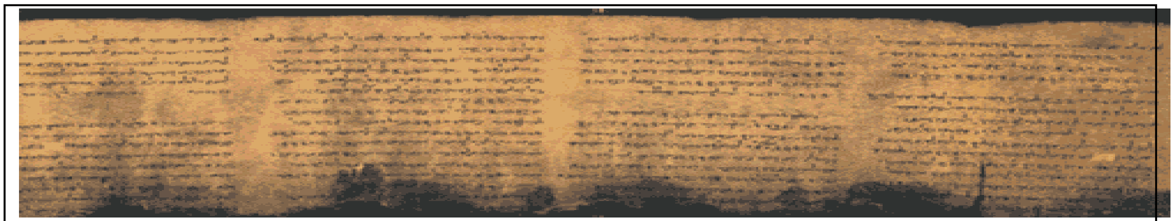
Introduction to Radioactive Decay and Half-Life:

^{14}C Dating

Archaeologists determine the approximate ages of many artifacts by a method called *carbon-14 (^{14}C) dating*. You may have heard of ^{14}C dating for such objects as the Dead Sea Scrolls, the Shroud of Turin, or prehistoric human remains. How does it work?



A portion of the Dead Sea Scrolls. Since paper and other plant-based writing surfaces are generally new when written on, Carbon-14 dating can help determine the ages of ancient documents.

Many chemical elements exist in several different forms, called *isotopes*, which differ from each other only in their number of neutrons per atom. Since chemical reactions depend on the electronic structure of atoms, different isotopes of the same element are essentially identical in their chemical behavior.

The most stable and by far the most common isotope of carbon, ^{12}C, has six protons and six neutrons in the nucleus of each carbon atom. However, there is another heavier isotope ^{14}C, with two extra neutrons per atom… and ^{14}C decays radioactively with a *half-life* of about 5,700 years.

Bones and fossils can be dated by Carbon-14 content.

^{14}C decays radioactively as follows:

$$\mathbf{^{14}C \rightarrow {}^{14}N + e^{-} + \overline{\nu}_e}$$

(^{14}C → ^{14}N + electron + electron antineutrino).

So the ^{14}C is converted into ordinary nitrogen, plus some other particles. The age of an object can then be related to the amount of ^{14}C that remains.

You might be wondering: if ^{14}C is radioactive and unstable, why isn't it all gone? Well, it turns out that ^{14}C is constantly being made by energetic cosmic ray particles (protons) interacting with atomic nuclei in the air:

cosmic ray proton + (atomic nucleus in the air) → ^{14}C + "other stuff"

where the “other stuff” is protons, neutrons, and other pieces of atomic debris. These cosmic ray particles have been bombarding the earth’s atmosphere at a steady rate throughout history, creating new ^{14}C nuclei in the air to replenish the ones that decay. Because of this process, an almost constant amount of ^{14}C is always available in the Earth's atmosphere.

After it is created by the cosmic ray event, the ^{14}C combines with oxygen to form molecules of carbon dioxide (CO_2). The CO_2 is incorporated into plant material through photosynthesis,

$$\mathbf{nCO_2 + nH_2O + energy \rightarrow (CH_2O)_n + nO_2}$$

and so living plants consist of carbon that contains the same fraction of ^{14}C (relative to ^{12}C) as the earth’s atmosphere. The plants we eat are recently grown and have this fraction of ^{14}C. If we eat animals, they also have ingested recently grown plants and contain this same abundance as well. So the carbon in our bodies contains this natural abundance of ^{14}C.

However, when we die, we stop ingesting plant and animal material and thereafter the ^{14}C in our body decays and the abundance decreases. The longer it has been since a person died, the lower the abundance of ^{14}C in their remains. This is the principle of ^{14}C dating.

So we have established that the ^{14}C in an artifact decays over time into ^{14}N. Each individual ^{14}C nucleus decays at a time we cannot predict, but if we have many nuclei (as in any macroscopic object), the number remaining is related to the radioactive half-life of about 5,700 years. The half-life is the time it takes for half of the existing ^{14}C to decay. Thus an object with half the natural amount of ^{14}C has been around for one half-life and is roughly 5,700 years old. An object with one-quarter the natural amount of ^{14}C has been through two half-lives, and is therefore about 11,400 years old. Object ages between about 1,000 and several 10,000’s of years can be determined by measuring ^{14}C abundances in this way.

By telling the story of ^{14}C dating here, we have explored the phenomenon of radioactive decay and of nuclear interactions in general. We have also introduced the concept of the half-life for an unstable nucleus or other radioactive particle. We will explore these concepts in more depth throughout the rest of this activity. You will then measure the half-life of a subatomic particle called the "muon," which lasts a lot less than 5,700 years (we don't have that long to spend on an activity)!

More details:

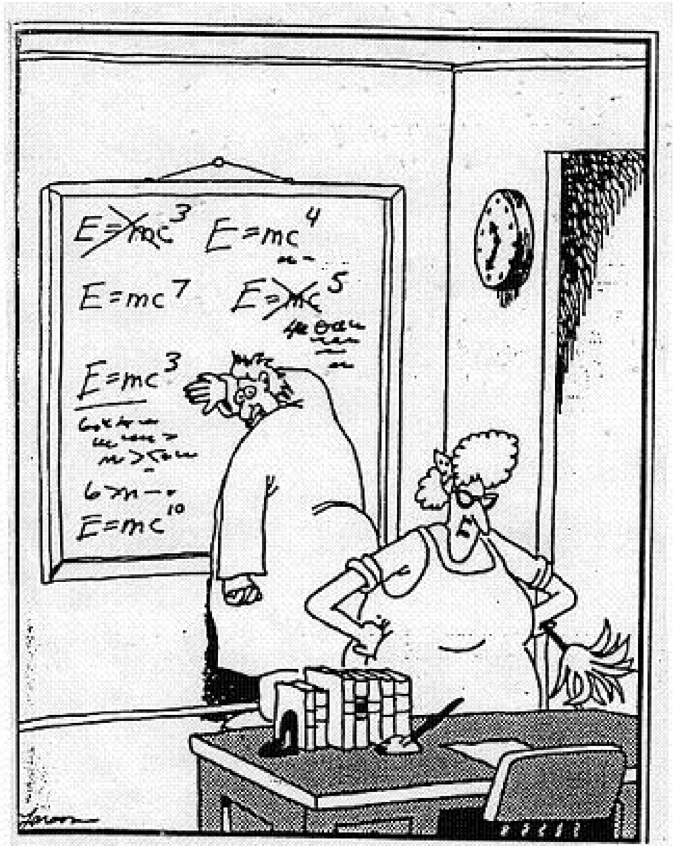
Notice ^{14}C has (Z=6 protons, N=8 neutrons) and ^{14}N has (Z=7 protons, N=7 neutrons), so in many ways the decay boils down to:

$$\mathbf{n \rightarrow p + e^- + \bar{\nu}_e}$$

or, if you are familiar with the quark structure of neutrons and protons,

$$\mathbf{d \rightarrow u + e^- + \bar{\nu}_e.}$$

The radioactive decay conserves electric charge (the electron antineutrino is a neutral particle). It does not conserve the number of atoms of each element, as a chemical reaction would. In fact, it destroys elementary particles and creates others. In the decay reaction above, the d (down quark) is not “made of” an up quark (u), an electron, and an antineutrino; the decay is not simply the separation of component pieces that were already there to begin with. Some particles are destroyed, and brand-new ones are created. There are several conservation rules that do hold, but conservation of electric charge is the only one tied to a property “ordinary” enough to appear in chemistry or in the experience of most non-physicists.



"Now that desk looks better. Everything's squared away, yessir, squaaaaaared away."

The radioactive decay process does conserve energy, but only if we are allowed to count mass as a type of energy and convert some of the original mass into other forms of energy according to the famous equation

$$\mathbf{E=mc^2}.$$

Even if the original ^{14}C is at rest, the particles produced in the decay can fly off with nonzero kinetic energy. This conversion back and forth between mass energy and other forms of energy is what nuclear reactions are all about.