Nuclear Chemistry Q & A (FAQ)

Why is this chapter on half-life being presented?
The purpose of this chapter is to explain the process of radioactive decay and its relationship to the concept of half-life. The primary intent is to demonstrate how the half-life of a radionuclide can be used in practical ways to "fingerprint" radioactive materials, to "date" organic materials, to estimate the age of the earth, and to optimize the medical benefits of radionuclide usage.

What is meant by the "decay" of a radionuclide?
Remember that a radionuclide represents an element with a particular combination of protons and neutrons (nucleons) in the nucleus of the atom. A radionuclide has an unstable combination of nucleons and emits radiation in the process of regaining stability. Reaching stability involves the process of radioactive decay. A decay, also known as a disintegration of a radioactive nuclide, entails a change from an unstable combination of neutrons and protons in the nucleus to a stable (or more stable) combination. The type of decay determines whether the ratio of neutrons to protons will increase or decrease to reach a more stable configuration. It also determines the type of radiation emitted.

How do radioactive atoms decay?
Radioactive atoms decay principally by alpha decay, negative beta emission, positron emission, and electron capture.

How does the neutron-to-proton number change for each of these decay types?
Alpha decay typically occurs in nuclei that are so big that they can't be stable. In alpha decay, the nucleus ejects a helium nucleus (alpha particle) composed of two neutrons and two protons, dropping the mass of the original nucleus by four mass units. This smaller nucleus is easier to keep in a stable form.

Beta decay?
In negative beta decay, the nucleus contains an excess of neutrons. To correct this unstable condition, a neutron is converted into a proton, which keeps the nucleus the same size (i.e., the same atomic mass) but increases the number of protons (and therefore the atomic number) by one. In the process of this conversion, a beta particle with a negative charge is then ejected from the nucleus.

What about positron decay?
In positron decay, the opposite situation occurs: the proton to neutron ratio is greater than desired. Accordingly, a proton is converted into a neutron and a beta particle (but with a positive charge!) is ejected.Again, the nucleus remains the same size, but the number of protons decreases by one.

And electron capture?
Electron capture results in the same outcome as positron decay in that, in this process, the nucleus stays the same size and the number of protons decreases by one. In this type of decay, however, the nucleus captures an electron and combines it with a proton to create a neutron. X-

rays are given off as other electrons surrounding the nucleus move around to account for the one that was lost.

Each one of these decay types may also involve the release of one or more photons of gamma radiation. These photons are pure energy given off by the nucleus in its process of achieving stability.

Does anything else occur during the decay process?
You may have noticed that the decay modes discussed above involve particles. Therefore, decay of a radionuclide results in a loss of mass. The mass is converted into energy (do you recall Einstein's equation?!) and released.

Is it possible to predict when a given radioactive atom will decay?
No, its not. The decay of an individual atom is a random event. However, it is possible to predict when decay will occur based on probability, particularly when there are a lot of radioactive atoms around. Fortunately, since atoms are so small, it doesn't take much radioactive material to represent a lot of atoms.

What is meant by the decay rate?
The decay rate is simply the number of radioactive atom decays occurring over a specified time.

Is there another designation for the decay rate?
Yes. The decay rate is conventionally known as the "activity" or "radioactivity" of a material, sample or medium.

What kinds of units are used to reflect activity or decay rate?
Units of activity include disintegration per second (dps), disintegration per minute (dpm), the curie (Ci), and the becquerel (Bq). Each of these units is a measure of the number of atoms occurring over a specified time. A curie of activity, for example, represents 37 billion atoms decaying every second (37 billion dps) - a very large number! - while one (1) becquerel is equivalent to a single atom decaying each second.

What factors can be used to characterize or "fingerprint" a radionuclide?
There are basically three factors that separate one radionuclide from another. These are its half-life, the particulate or photon energy associated with its decay, and the type of emission

What do you mean by half-life?
A half-life is defined as the amount of time required for one-half or 50% of the radioactive atoms to undergo a radioactive decay. This is also known as the "radioactive" or "physical" half-life. Every radioactive element has a specific half-life associated with it.

Since the half-life is defined for the time at which 50% of the atoms have decayed, why can't we predict when a particular atom of that element will decay?
The concept of half-life relies on a lot of radioactive atoms being present. As an example, imagine you could see inside a bag of popcorn as you heat it inside your microwave oven. While you could not predict when (or if) a particular kernel would "pop," you would observe that after

2-3 minutes, all the kernels that were going to pop had in fact done so. In a similar way, we know that, when dealing with a lot of radioactive atoms, we can accurately predict when one-half of them have decayed, even if we do not know the exact time that a particular atom will do so.

What else can you tell me about the half life of atoms?
Half-lives range from fractions of a second to billions of years. For example, Carbon-14 (C-14), a naturally occurring radionuclide, has a half-life of 5,730 years. After this amount of time passes, half of the initial amount of C-14 is present. Therefore, if you began with two (2) curies of C-14, one-half of that amount, or one curie, would be present 5,730 years later. After two (2) half-lives, one-fourth of the initial activity, or 0.5 curies, would be left. After three (3) half-lives, which is more than 17,000 years later, one-eighth of the original C-14 activity, or 0.25 curies, would remain, and so forth.

Well, 5,730 years seems like a long time to wait for the original C-14 activity to diminish by 50%.
You're right. This points out the fact that the rate of decay of short-lived materials is much faster than for their long-lived counterparts.

Can I make the process hurry along?
Unfortunately, no. Each radionuclide has its own characteristic half-life. No operation or process of any kind (i.e., chemical or physical) has ever been shown to change the rate at which a radionuclide decays.

Where can I find a listing of half lives of various radionuclides?
Values for individual half-lives can be found in the literature. This includes health physics textbooks and the Chart of the Nuclides, a copy of which appears in the "Links" section of the IEM web page (red button on the left), under the category entitled "Gadgets and Tools". In addition, the "Tool Box" section of the IEM web page contains a listing of half-lives for commonly-encountered radionuclides, in order by element name.

What is meant by the term specific activity?
The term "specific activity" refers to the activity of a particular radioactive element (i.e., the number of decays per time) divided by the mass of material in which it exists. Put another way, the specific activity defines the relationship between the activity and the mass of material. Units for specific activity include the curie per gram (Ci/g) and the becquerel per kilogram (Bq/kg), etc.

How is specific activity related to half-life?
Half-life has a profound effect on the specific activity. The shorter the half-life, the higher the specific activity. As a short-lived radionuclide undergoes the process of radioactive decay, atoms of the radionuclide in question emit radioactivity (alpha particles, beta particles, etc.) frequently as they decay. The higher this rate of decay (activity) while maintaining a (nearly) constant mass, the higher the specific activity. On the other hand, atoms of a long-lived radionuclide (one with a long half-life) do not decay nearly as frequently. Therefore, a lower rate of decay within a specified mass of material results in a lower specific activity.

What are some examples of radionuclides with low specific activities?
Many radionuclides have half-lives of millions to billions of years. Uranium-238 (U-238), a naturally occurring radionuclide, has a half-life of 4.5 billion years. Potassium-40 (K-40), another naturally occurring radionuclide found in the air, water, soil (and therefore in foodstuffs and consequently in our bodies), has a half-life of approximately 1.3 billion years. Plutonium-239 (Pu-239), a man-made element, has a half-life of only 240,000 years. Because of their long half-lives, each of these radionuclides, and many others like them, do not decay into other elements on a very frequent basis. For this reason, their specific activities are considered to be low.

What about high specific activities?
Radionuclides with high specific activities must have short half-lives (seconds, minutes, hours, or, at the most, a few years). Many radionuclides have short half lives. For example, Nitrogen-16 (N-16), a radionuclide associated with nuclear power plant operations, has a half-life on the order of seven (7) seconds. Talk about a high rate of decay!

Are there other examples?
The metastable form of Technetium-99 (Tc-99m) and Iodine-131 (I-131), both used in nuclear medicine procedures, have half-lives of only six (6) hours and eight (8) days, respectively. Tritium (Hydrogen-3 or H-3), a radioactive isotope of hydrogen and one that is produced both naturally and for man-made purposes, has a half-life of 12.3 years. These radionuclides with short (or relatively short) half-lives decay on a much more frequent basis than their longer half-life counterparts. When each of their respective activities is divided by the same mass (a gram of material, for example), a high specific activity results.

So half-life and mass have some sort of a relationship?
Yes. To put this concept in a slightly different perspective, take the case of the two radionuclides Sulfur-35 (S-35) and Phosphorus-32 (P-32). S-35 and P-32 have half-lives of 87 days and 14.3 days, respectively. Therefore, the P-32 decays approximately six (6) times faster than the sulfur. On a mass basis, then, one-sixth (1/6) of a gram of P-32 is essentially equivalent to one (1) gram of S-35 in terms of radioactivity!

Where can I find a list of the specific activities of the various radionuclides?
The best place to start is the IEM "Tool Box" (on the left), under the section entitled "Specific Activities". You'll find a pretty comprehensive listing there.

Can an element's half life be used to distinguish it from other elements?
Yes, in many cases it can. Successful radionuclide identification is largely determined by the three factors noted previously (half-life, energy, and type of decay). Since many radionuclides have unique half-lives, the half-life can be used for identification purposes. For example, if a sample containing an unknown radionuclide is counted using an appropriate radiation detector, and the observed activity decreases by one-half of the initial activity after fourteen (14) days, the radionuclide is likely P-32, a pure beta emitter (it only decays by beta emission) with a half-life of 14.3 days.

Are there times when this doesn't work?
Yes. Some radionuclides do have similar half-lives which would complicate the identification process. However, in these cases, the energies of the radiations they emit during the decay process will differ and can be used to establish the radionuclide's identity.

How can the concept of half-life be used to determine the age of organic materials?
Radiometric dating is a widely used technique that utilizes the half-life of radioactive elements as a means to estimate the age of various materials. Several approaches are used. Perhaps the most widely publicized has been radiocarbon dating.

Tell me more about radiometric dating.
In the early 19th century, only a relative time scale (versus an absolute scale) could be used by geologists. They could not determine the absolute amount of time a rock or fossil had been in existence because they had no way to measure their ages. Then, in 1905, less than 10 years after radioactivity was discovered by Henri Becquerel, radiometric dating, using the principle of radioactive decay to measure the age of rocks and minerals, was introduced.

Sounds impressive!
Considering that isotopes and decay rates were not known at this time is certainly cause for amazement about these early studies!

So how does radiometric dating work?
Radiometric dating relies on the use of radioactive elements as "geological clocks". Since each element decays at its own characteristic rate, geologists can estimate the length of time over which the decays have occurred by measuring the amount of the radioactive parent present relative to the amount of the stable daughter. Put another way, the ratio of parent to daughter can tell us the number of half-lives, which in turn, can be used to find the age in years. As an example, if an equal number of parent and daughter atoms exist, then one-half life has passed.

How does radiocarbon dating work?
Carbon-14 (C-14), a radioactive isotope of carbon, is naturally produced in the upper atmosphere through bombardment of Nitrogen-14 (N-14) with cosmic rays. The C-14 is then rapidly oxidized to radioactive carbon dioxide gas which is absorbed and used by plants. This serves as its introduction into the food chain.

Then what?
Radiocarbon dating relies on the assumption that C-14 exists in an "equilibrium" concentration in the carbon of living biological materials, meaning the ratio of C-14 in the body to that of stable Carbon, or C-12, stays constant. When a plant or animal dies, it ceases breathing, eating, and/or absorbing carbon (and therefore C-14). Thus, the C-14-to-C-12 ratio is no longer fixed. The C-14 begins to decay back into N-14, resulting in a decrease in the C-14 concentration based on its half-life (a 50% reduction every 5,730 years). Since the rate of decay is known, the concentration (specific activity) of C-14 in organic (carbon-containing) materials can be measured and used to calculate the date that the plant or animal died.

Wow. Does it work all the time?
Yes, but only on materials that contain carbon , and only on materials that were once living.

Where is C-14 dating used?
Radiocarbon dating has been used to determine the age of certain fossilized bones. In addition, this technique has been applied with great success in archaeological dating and dating associated with the ice ages.

Are there any shortcomings of this method?
Yes. The C-14-to-C-12 ratio has not remained constant with time as determined by measuring the levels of radiocarbon in tree rings. The fact that C-14 is also produced through man-made activities is another confounding factor. With the beginning of the industrial age, large quantities of coal have been burned. Coal is very old, meaning that the ratio of C-14 to C-12 is essentially nonexistent. This has the effect of diluting the ratio in the atmosphere following carbon dioxide releases. Without making a series of corrections to account for these confounding factors, the resulting C-14 age determination will be in error.

Any other limitations?
Just one. It has also been stated that this method can only be used on materials less than 50,000-70,000 years old. Beyond that point, there are so few C-14 atoms remaining in the sample that it becomes difficult to measure them.

Can you provide other examples of radiometric dating?
Certainly. Potassium-Argon dating is another form. It relies on the decay of Potassium-40 (K-40), a naturally occurring radionuclide, to Argon- 40 (Ar-40), to place an age on rocks and sediments. This method was used recently to estimate the age at which the eruption of the volcano, Vesuvius, occurred in the ancient Roman city of Pompeii. (Historians place the eruption around 79 A.D. or 1,919 years ago, while potassium-argon dating estimated this event occurred 1,926 years ago, an error of less than one percent , but an error nonetheless!)

Are there other types?
Rubidium-strontium dating, which relies on the decay of Rubidium-87 to Strontium-87, has been used to date very old terrestrial rocks as well as lunar samples. Thorium-230 (Th-230) has been utilized to date oceanic sediments that are older than the useful range of radiocarbon techniques. The fission-track method relies on the paths, or tracks, produced by charged particles traversing a mineral's crystal lattice as a result of spontaneous fission by uranium impurities.

Anything more?
Yes indeed! There are still other interesting methods used in age-dating. One of these is known as thermoluminescence.

What is thermoluminescence and how has it been used?
Taken separately, the word "thermo" implies heating, while the word "luminescence" refers to light. In brief, a thermoluminescent material stores radiation energy once it is absorbed. Upon heating the material, this "trapped" energy is released and emits light. The amount of light can be related to the radiation dose received over time or, for the purposes of this chapter, to the age of

the material if the half-life is known (to account for radioactive decay over periods of up to hundreds of thousands of years).

Can you provide an example?
Yes. Following the atomic bomb blasts in Hiroshima and Nagasaki Japan, samples of ceramic roofing tiles, ornamental tiles and brick from various locations within one (1) kilometer (km) of ground zero were collected, broken down into much smaller fragments, and heated. The amount of light released was used as a measure of the radiation dose at the location from which the samples were taken. These doses can then be assigned to the survivors based on where they were when the bombs were dropped.

Why are radionuclides with short half-lives used most often in medical applications?
Medical procedures are designed, of course, to help the patient. When certain procedures are performed utilizing radioactivity, it is advantageous and important from a health perspective to use radionuclides that satisfy the desired diagnostic or treatment objective and then decay away before they expose the patient to unnecessary amounts of radiation.

Can you give me an example?
Radionuclides such as Tc-99m, with a half-life of six (6) hours, are routinely used in bone scans because the medical objective is successfully reached while the amount of radioactivity diminishes rapidly. Another example is the treatment for thyroid disorders that utilizes I-131 with a short half-life of eight (8) days. Many other examples with this same objective in mind are used in the medical field.

Are long-lived radionuclides ever used in medical applications?
Yes. There are cases where using short-lived materials will simply not accomplish the desired medical objective. A classic example involves the use of Pu-238 as the power supply in cardiac (heart) pacemakers. This radionuclide has a pretty long half-life (87.7 years) and a relatively high specific activity - two worthwhile attributes for this application. It is inserted into the battery as a sealed source in the patient to provide power to the pacemaker. Using a sealed source means that the radioactive material stays where it was put. It is readily apparent that using shorter-lived radionuclides for this purpose would not be advantageous because the sources would have to be replaced on a routine basis. And every replacement source is another surgery!

Is Pu-238 used in non-medical applications?
Yes, Pu-238 is used as a power source in space missions, such as the relatively recent NASA Galileo launch. The energy associated with the decay of this radionuclide is converted into electricity to power the probe to its desired destination. NASA used this type of power supply because the probe would be traveling so far from the Sun that solar power couldn't be used. As with the medical applications discussed previously, the half-life and associated specific activity merits its use in this application.

I've heard the term "biological half life" before. Is it different from the physical half-life we have been discussing?
Most definitely. In contrast to the radiological (physical) half-life, the biological half-life is a

measure of how long it takes to eliminate half of the radioactivity taken into the body by biological processes (e.g., excretion).

Can you give me an example?

Be glad to. Cesium-137 (Cs- 137) has a physical half-life of approximately 30 years. Left outside the body, half of the initial radioactivity will decay or disappear in that time frame. Inside the body, however, Cs-137 has a biological half-life of only seventy (70) days. This means that biological processes significantly accelerate the rate of clearance associated with this radionuclide in comparison to the radiological half-life. Half of the radioactivity will be gone after 70 days, another half of the radioactivity in another 70 days, etc.

What is an effective half-life?

If radioactivity is taken into the body, decay of the radionuclide will occur by both physical and biological means. The effective half-life is a measure of the combined influences of these two distinct half-lives. In the case of the Cs-137 example, the radiological and biological half-lives are thirty (30) years and seventy (70) days, respectively. The effective half-life in this instance is slightly less than seventy (70) days. It is important to note that the effective half-life is always lower than either the biological or the physical half-life.