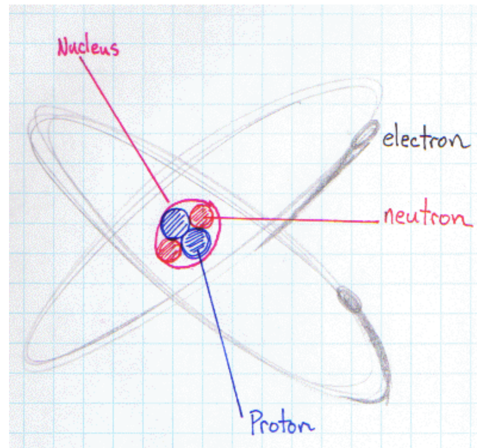
DAY 26

Summary of Primary Topics Covered

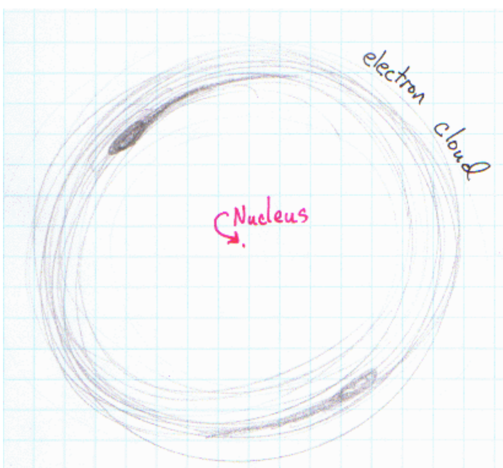
The Nucleus of an Atom

An atom consists of a nucleus containing protons and neutrons, with electrons around the nucleus. These three *subatomic particles* are the three fundamental building blocks from which all atoms are formed.



The electrons are bound to the atom by electrical forces – by the attraction of the negatively charged electrons to the positively charged nucleus (*opposite charges attract one another*). The picture at right is the typical picture of an atom that you've probably seen since 2nd grade.

There is a problem with that picture, however – it makes the nucleus look a lot larger than it really is.



In actuality the nucleus of an atom is tiny. The atom's size comes from the electrons. However, the electrons contain very little of the atom's mass.

	Symbol	Mass	Charge
proton	p	1.00728 u	1 e
neutron	n	1.00866 u	0
electron	E	0.00055 u	-1 e

Here *u* is an *atomic mass unit*. $1\ u = 1.6605 \times 10^{-27}$ kg. If you recall from early in the semester, *e* is a unit of electrical charge called the elemental charge and simply denotes the charge on an electron. Since the proton and electron have equal but opposite charges, if an atom has equal numbers of protons and electrons its total charge is zero and it is said to be electrically neutral.

The number of protons in a nucleus defines what type of nucleus it is. One proton is Hydrogen. Two is Helium. Six protons is a Carbon nucleus. Twenty-six protons is Iron. This is called the *Atomic Number*. It is usually designated with a letter *Z*.

The number of neutrons in a nucleus is called the Neutron Number (*N*). The total number of protons and neutrons in the nucleus is the Mass Number (*A*). It is also referred to as the number of nucleons (particles that reside in the nucleus are called nucleons).

A = Z + N

Nuclei are represented by their Mass Number, Atomic Number, and chemical symbol (which you look up on a Periodic Table of Elements):

${}^{1}_{1}\mathrm{H}$	${}^{4}_{2}\mathrm{He}$	${}^{52}_{24}\mathrm{Cr}$	${}^{222}_{86}\mathrm{Rn}$
1 proton	2 protons	24 protons	136 neutrons
0 neutrons	2 neutrons	28 neutrons	86 protons
Hydrogen – 1	**Helium – 4**	**Chromium – 52**	**Radon – 222**

Nuclei can have different numbers of neutrons. Nuclei with different numbers of neutrons but the same numbers of protons are called *isotopes*:

${}^{238}_{92}\mathrm{U}$	${}^{235}_{92}\mathrm{U}$	${}^{234}_{92}\mathrm{U}$
92 protons	92 protons	92 protons
146 neutrons	143 neutrons	142 neutrons
Uranium – 238	**Uranium – 235**	**Uranium – 234**
U – 238	**U – 235**	**U – 234**

Each of these is an isotope of Uranium.

Similarly

${}^{4}_{2}\mathrm{He}$	${}^{3}_{2}\mathrm{He}$
2 protons	2 protons
2 neutrons	1 neutron
Helium – 4	**Helium – 3**
He – 4	**He – 3**

Are both Helium. Both act like Helium. If you filled one balloon with He – 4, and the other with He – 3, both would float and both would make you sound like Donald Duck if you inhaled them.

Stable and Unstable Nuclei

Electrical repulsion between protons (*like charges repel one another*) means that every nucleus with more than one proton has to have some force that acts like glue to hold the nucleus together. This force, called the *Strong Nuclear Force*, acts through the presence of neutrons. This "neutron glue" holds the nucleus together. But like with "super glue", where too much super glue or too little super glue results in a bad bond, too many or two few neutrons will result in a nucleus that will eventually come apart. Furthermore, no amount of neutron glue will hold together a nucleus with Z > 83. All nuclei with more than 83 protons will eventually come apart.

Scientists have found that if nuclei are small, they tend to be stable when they have near-equal numbers of protons and neutrons. However, as they get larger, more and more neutrons per proton are required to hold the nucleus together. Finally, for Z > 83, no number of neutrons will hold the nucleus together in a stable fashion.

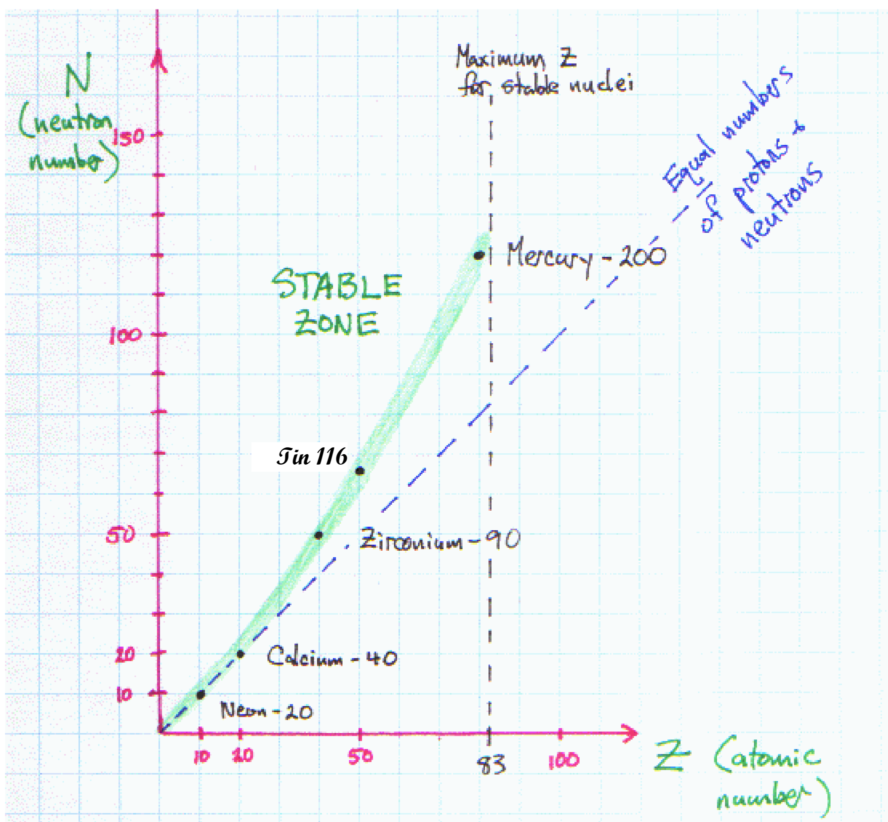
Neon – 20
10 protons
10 neutrons
neutrons per proton: 1.00

Calcium – 40
20 protons
20 neutrons
neutrons per proton: 1.00

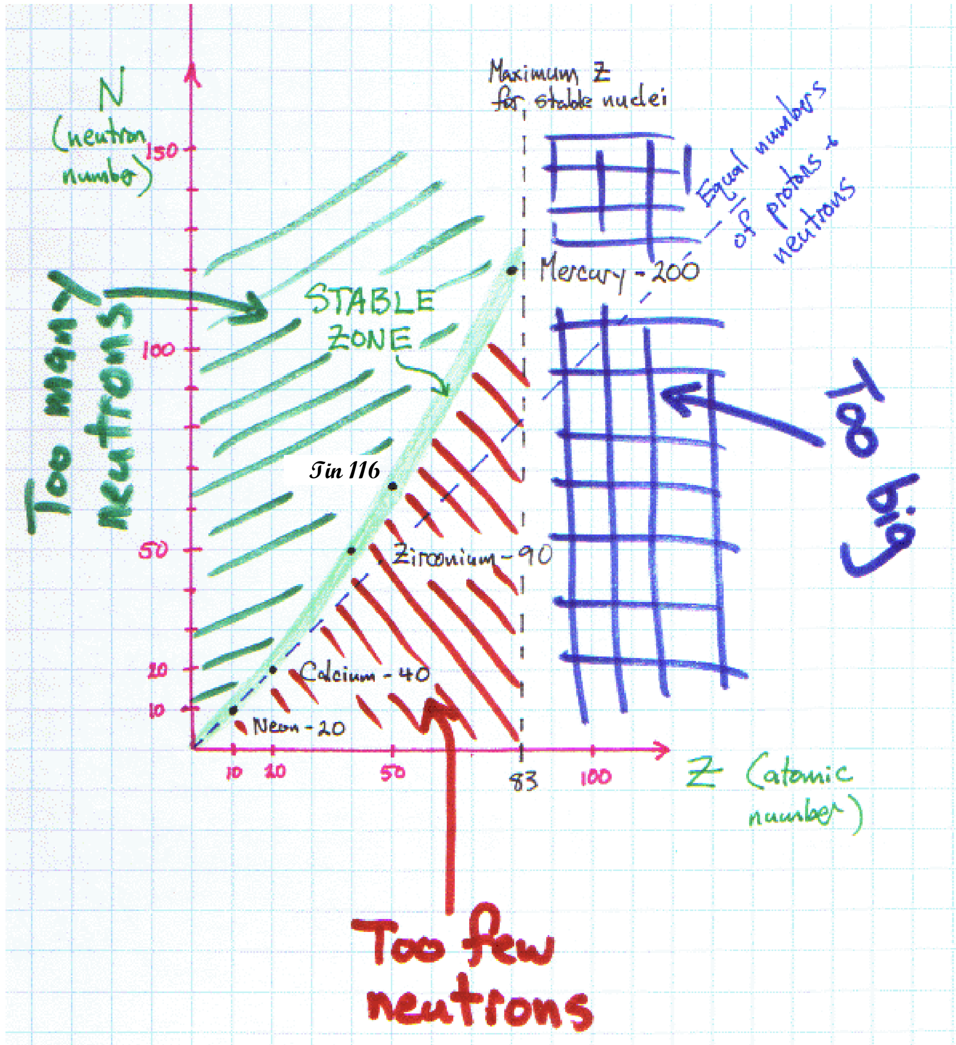
Zirconium – 90
40 protons
50 neutrons
neutrons per proton: 1.25

Tin – 116
50 protons
66 neutrons
neutrons per proton: 1.32

Mercury – 200
80 protons
120 neutrons
neutrons per proton: 1.50



Thus there is a small range of possible combinations of neutrons and protons that yields stable nuclei. Anything else has too many neutrons, too few neutrons, or is simply too big a nucleus to be stable.

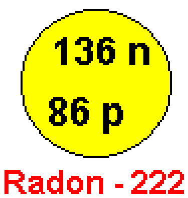


It must be noted that physicists currently believe that, if left alone, **stable nuclei last forever** -- as long as the universe has existed so far and far longer. The available evidence currently suggests that pretty much the only nuclei formed at the beginning of the universe were Hydrogen and Helium. Everything else was formed via nuclear fusion either inside stars or in the explosion of stars ("*supernovae*"). Thus all the iron and calcium and carbon and oxygen that makes up our bodies was formed in a star billions of years ago - before the Earth was formed.

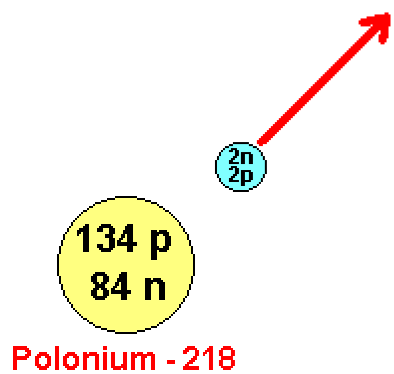
An unstable nucleus is simply a nucleus that does not last forever. Some unstable nuclei might last milliseconds. Others may last for millions of years. But long-lived or short-lived, they are still unstable.

Unstable Nuclei and Radioactivity

Unstable nuclei will eventually break apart, seeking to become stable. For instance, Radon – 222 (the infamous "Radon Gas" you may have heard about) contains 86 protons and 136 neutrons. It is too big (Z > 83) to be stable. So what happens? Eventually -- maybe real soon, maybe a long time from now, but eventually -- it will spit out a couple of protons and neutrons in an effort to get smaller.



This small particle carries kinetic energy, like a little bullet. What is left behind is a smaller nucleus (although in this case still not stable). The little bullet is dangerous to life because it can damage the structures in living cells. It can also heat up and degrade even non-living matter. This is the nuclear "radiation" you hear about. An unstable nucleus is "*radioactive*".



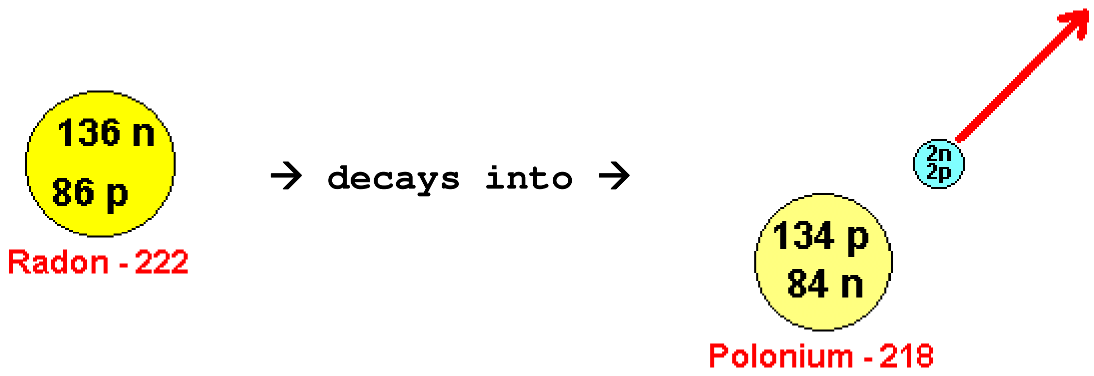
Decay Modes of Unstable Nuclei

Unstable nuclei decay via a number of different methods. There are three principle methods:

- **α decay** ("alpha" decay), in which the unstable nucleus ejects two protons and two neutrons (a helium nucleus, also called an α particle).
- **β decay** ("beta" decay), which involves the unstable nucleus ejects or absorbing an electron (or possibly a *positron*).
- **γ decay** ("gamma" decay), which involves the unstable nucleus ejecting a *photon*.

α Decay

α decay usually occurs in nuclei that are unstable due to the fact that they are too large. For instance, the example given in which Radon-222 decays into Polonium-218 is an example of α decay:



The Radon loses two protons and two neutrons (a Helium nucleus, which is also called an α particle). This can be written via a nuclear reaction equation as

$$^{222}_{86}\mathrm{Rn} \longrightarrow {}^{218}_{84}\mathrm{Po} + {}^{4}_{2}\alpha$$

Note that the numbers above the element symbols must add up to the same value on both sides of the equation (218 + 4 = 222). These are the Mass Numbers and they represent the mass present in the decay reaction. Also the numbers below the symbols must add up to the same value on both sides of the equation (84 + 2 = 86). These are the Atomic Numbers and they represent the charge present in the decay equation. The total mass and charge in the system must stay essentially constant in a reaction.

β Decay

β decay usually occurs in nuclei that are unstable due to the fact that they have too many or too few neutrons. There are several different types of β decay.

Ordinary β decay, known as β^- decay, tends to occur in nuclei that have too many neutrons. Inside the nucleus, a neutron splits into a proton and an electron. The result is that the nucleus gains a proton, and loses a neutron. The decay process launches the electron out of the nucleus at high speed. This high-speed electron is called a β particle. Sodium-24 undergoes β^- becay:

$$^{24}_{11}\mathrm{Na} \longrightarrow {}^{24}_{12}\mathrm{Mg} + {}^{0}_{-1}\beta + {}^{0}_{0}\overline{\nu}$$

The daughter nucleus is Magnesium-24. The last particle is a type of *neutrino* - a particle with very little mass and no charge.

On the other hand, in a nucleus that is unstable because it has too few neutrons, a proton can split into a neutron and a particle called a *positron*. A positron is identical to an electron except that it has a positive charge. Positrons are part of a class of material known as *anti-matter*. The result is that the nucleus gains a neutron, and loses a proton. The decay process launches the positron out of the nucleus at high speed. This high-speed electron is called a β^+ particle. Potassium-37 undergoes β^+ becay:

$$^{37}_{19}\mathrm{K} \longrightarrow {}^{37}_{18}\mathrm{Ar} + {}^{0}_{+1}\beta + {}^{0}_{0}\nu$$

The daughter nucleus is Argon-37. Again, a type of neutrino is created in this reaction.

It is also possible for a nucleus to capture one of the electrons that orbit it. The electron combines with a proton in the nucleus to create a neutron. The end result -- one less proton, one more neutron -- is the same as in β^+ decay. This is called electron capture (sometimes written as EC or ε). Potassium-37 can also decay via EC.

$$^{37}_{19}\mathrm{K} + {}^{0}_{-1}\mathrm{e} \longrightarrow {}^{37}_{18}\mathrm{Ar} + {}^{0}_{0}\nu$$

The daughter nucleus and the neutrino are the same as in β^+ decay.

γ Decay

γ decay occurs in nuclei that are unstable due to the fact that they have too much energy. Such nuclei are said to be in an *excited state* and are unstable until they lose their excess energy. The energy is lost via a high-energy *photon* or γ-ray. Photons are particles of electromagnetic energy - the same energy involved in heat transfer by radiation. Often nuclei are excited following another decay. For instance, Boron-12 decays into excited Carbon-12. The Carbon-12 then decays via γ decay.

$$^{12}_{5}B \longrightarrow {}^{12}_{6}C^{*} + {}^{0}_{-1}\beta + {}^{0}_{0}\bar{\nu}$$

$$^{12}_{6}C^{*} \longrightarrow {}^{12}_{6}C + {}^{0}_{0}\gamma$$

The γ-ray (photon) has zero mass and zero charge. It is pure energy.

Half-Life

"Half-lives" can be used to describe just how unstable a radioactive nucleus is. When dealing with radioisotopes, "half-life" can be thought of in two ways.

First, the decay of an individual nucleus is a random process. Just like it is impossible to predict whether a coin that is tossed and allowed to hit the ground will come up heads, or whether a die that is rolled will come up "1", it is impossible to predict when an individual nucleus will decay. However, some nuclei are more likely to decay than others. If there is a 50% chance that nucleus *A* will decay in the next 10 minutes, then we say that nucleus *A* has a half-life of 10 minutes ($T_{1/2}$ = 10 min). If there is a 50% chance that nucleus *B* will decay in the next 2 hours, then we say that nucleus *B* has a half-life of 2 hours ($T_{1/2}$ = 2 hr). In this example, chances are *A* will decay before *B*. However, that is just a probability. *B* may decay first. *A* may not decay for days; *B* may decay immediately. With individual nuclei, nothing can be determined with certainty.

However, if you get many nuclei together you can make predictions about how they will behave. If you have 10,000 nuclei with $T_{1/2}$ = 10 minutes, you may not be able to tell which individual nuclei will decay, but you can expect that half of the 10,000 will decay in the next 10 minutes. This produces an *exponential* decay process.

If we are familiar with the exponential function (and the natural logarithm function) we can express the decay of unstable nuclei in terms of an equation:

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

N_0 is the number of nuclei you start with, N is the number remaining after time t. λ is a constant related to the half-life known as the *decay constant*.

When t = $T_{1/2}$, N = ½ N_0. Plugging these into the equation I can find the relationship between λ and $T_{1/2}$:

$$\lambda = \frac{\ln 2}{T_{1/2}} = \frac{0.693}{T_{1/2}}$$

Example Problem #1:

Identify the nucleus that contains 79 protons and 118 neutrons.

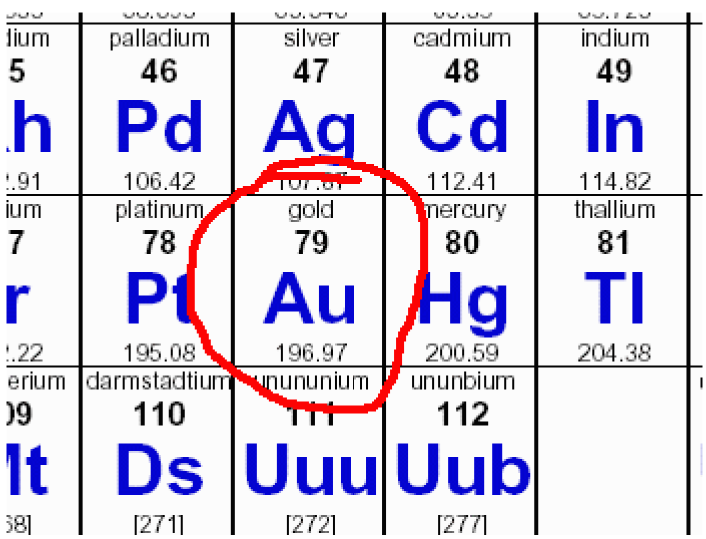
Solution:

79 protons means an Atomic Number of 79 (Z = 79). I get out my Periodic Table (there's a couple on the class web page) and look that up.

Ah – it's gold. The neutron number is N = 118, so the Mass Number (A) is

A = Z + N = 79 + 118 = 197.

So my nucleus is $^{197}_{79}\mathrm{Au}$ or **Au – 197**.



Example Problem #2:

Look at isotopes of Helium. Find all unstable isotopes that undergo beta decay, write out their decay equations, and state whether you think the daughters forms by these decays are likely to be stable.

Solution:

Looking up Helium in the on-line Periodic Table with Isotope Info I find that there are two isotopes of Helium that β decay (He-6 and He-8):

Isotopes of Helium (Z=2)

Click on an isotope to get more information about its decay

Isotope	Half-life	Spin Parity	Decay Mode(s) or Abunda
^{3}He	stable	1/2+	%Abundance=0.000137 3
^{4}He	stable	0+	%Abundance=99.999863 3
^{5}He	0.60 MeV	3/2-	%N=100
^{6}He	806.7 ms	0+	%B-=100
^{7}He	160 keV	(3/2)-	%N=100
^{8}He	119.0 ms	0+	%B-=100, %B-N=16 1
^{9}He	0.30 MeV	(1/2-)	%N=100
^{10}He	0.3 MeV	0+	%N=100

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Doing He-6 first:

$$^{6}_{2}He \rightarrow ^{6}_{3}Li + ^{0}_{-1}\beta + ^{0}_{0}\bar{\nu}$$

And since this Lithium nucleus has equal numbers of protons and neutrons (and is small) it will probably be stable.

Now for He-8:

$$^{8}_{2}He \rightarrow ^{8}_{3}Li + ^{0}_{-1}\beta + ^{0}_{0}\bar{\nu}$$

The Lithium has too many neutrons and is probably not stable.

Example Problem #3:

Radioactive Carbon-14 is used in dating old organic material (wood, bones, etc.). Living things take in a certain amount of C-14 as well as normal stable Carbon (C-12). By comparing the amount of C-14 in dead material to living material, one can determine how old it is.

A crude axe handle is found in a cave that has paintings in it from "cave men". The handle has only 1/8 the C-14 of living wood. How old is it? C-14 has a half-life of approximately 5700 years.

Solution:

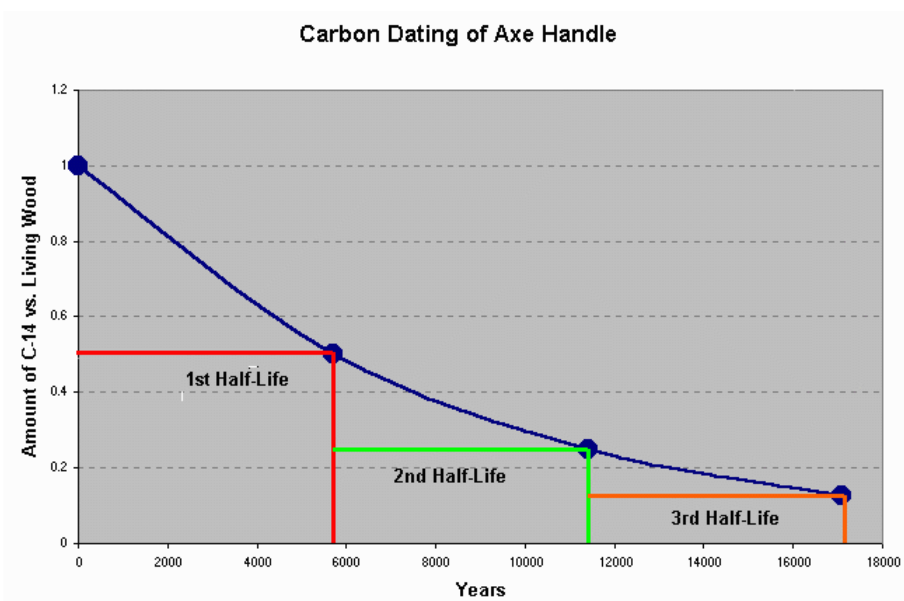
When the tree from which the handle is made was first cut down, it had the normal amount of C-14 vs. C-12. However, once it died, it stopped taking in C-14. The C-14 decayed, while the C-12 didn't.

After one half-life (5700 years) the axe handle would have ½ as much C-14 as living wood.

After another 5700 years the axe handle would have ¼ as much C-14 as living wood.

After another 5700 years the axe handle would have 1/8 as much C-14 as living wood.

So the axe handle is 5700 + 5700 + 5700 = 17,100 years old.



Example Problem #4:

Cobalt-60 decays into stable Nickel-60. Cobalt-60 has a half-life 5.271 years. How long will it take a sample of Co-60 to decay to the point where 99.95% of it has turned into Ni-60?

If 99.95% has turned into Ni-60 then only 0.05% of the original sample remains.

$N = 0.05\% \, N_o$ or $N = 0.0005 \, N_o$.

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

$\lambda = \ln 2/T_{1/2} = .693/(5.271 \text{ yr}) = 0.1315 \text{ 1/yr}$

$$0.0005 N_0 = N_0 e^{-0.1315 t}$$

$$0.0005 = e^{-0.1315 t}$$

$$\ln(0.0005) = \ln(e^{-0.1315 t})$$

-7.601 = -0.1315 t

t = 57.8 years