Nuclear Basics

Nuclear Chem covers tables N and O, radioactive isotopes, half lives, natural transmutation, artificial transmutation, fission + fusion reactions, nuclear power, carbon dating, fossil dating, medicinal uses for nuclear materials, atomic bombs, how the Sun works, and the Pro's and Con's about nuclear energy.

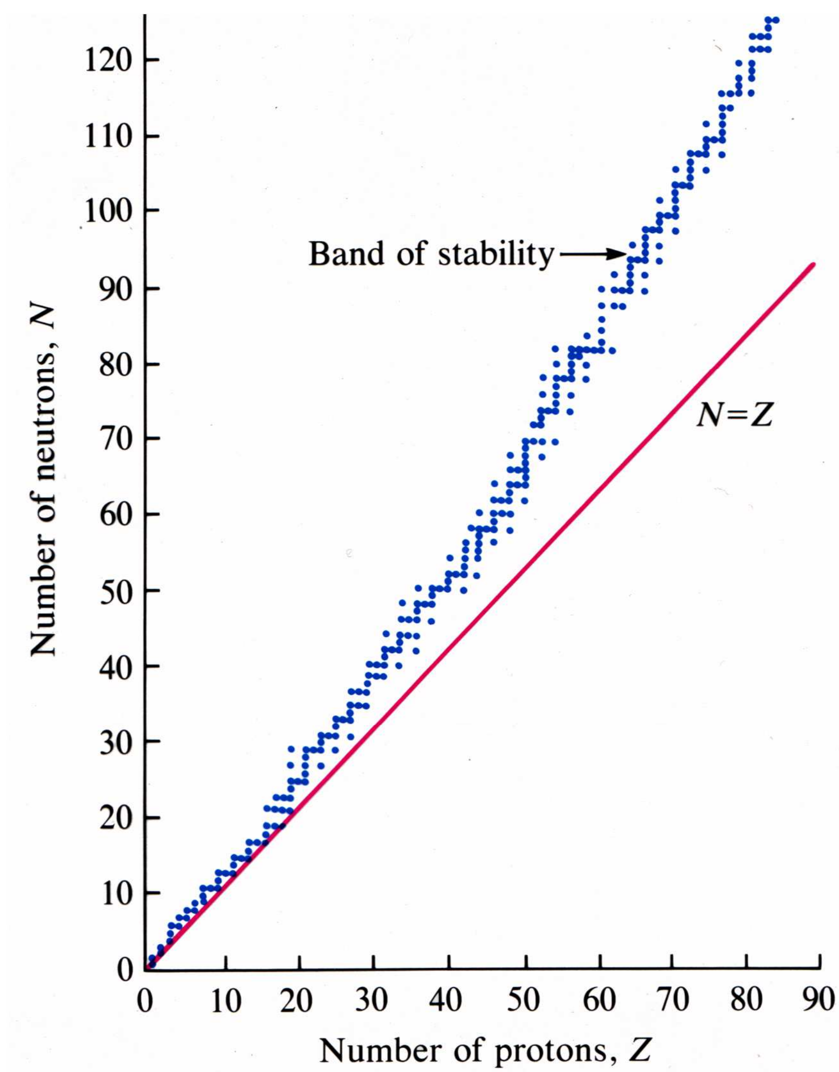
There are 118 atoms on the periodic table, and there are nearly 1500 isotopes. Each element has many "kinds" of atoms, with different numbers of neutrons and different masses. Most isotopes are stable, nearly 1300 of them. But about 200 of the isotopes are not stable. What might make them stable or not, it's the ratio of neutrons to protons that determines this. There is not one ratio that is stable, when atoms are smaller than calcium, the stable ratio of neutrons to protons is about 1:1. When atoms get bigger, the stable ratio adjusts too, increasing to about 1½:1 for larger atoms. Any ratios that are outside this "normally stable" ratio are considered to be unstable. This graph shows the stable ratios, and the line represents the 1:1 ratio. Atoms with fewer protons (smaller atoms) have stable ratios along this 1:1 line, but as the atoms get bigger, the stable ratio changes.

Most atoms are stable, they have a "normal" ratio of neutrons to protons. For the smaller atoms this ratio is, or is close to 1:1, but as the atoms increase in size, the ratio of $n^{\circ}:p^{+}$ increases.

My favorite atom Mercury is stable with 121 neutrons and just 80 protons, 121:80 is approximately a 1½ neutrons:1 proton ratio

Neutron/Proton Ratio of the Atoms.

Blue is stable, the red line is a 1:1 ratio

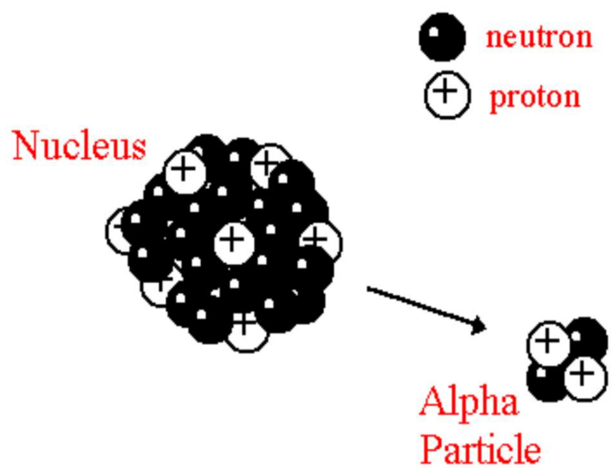


To become stable, these unstable nuclei will emit radiation, parts of their nucleus, to change this ratio of neutrons to protons to some other, hopefully more stable ratio. Sometimes an unstable atom only emits radiation particles one time, and they get a stable nucleus and the radioactive part of their "life" is over. Sometimes it takes more than one step, it must emit radiation more than one time, to keep changing until it gets stable.

Each radioactive (unstable) isotope emits a particular type of radiation. They do it exactly the same way, and at a predictable rate. If an isotope emits radiation particles but ends up a "new" radioisotope, it might emit the same, or it might emit a different kind of radiation particle. These processes are all known and tabulated for us. Although there are about 200 kinds of radioactive isotopes, there are only 24 listed in table N. Once you get the hang of how each kind of radiation particle emission changes the nucleus, you can apply this process to other isotopes you might meet in class or on the regents exam.

There are several forms of radiation, and sometimes certain unstable nuclei emit more than one kind of radiation at a time, or different kinds in a series of changes they undergo in the process to become stable. The picture here shows how an alpha particle is emitted by the nucleus of an unknown unstable isotope.

When an atom changes by emitting radioactivity (particles or energy or both), this is called natural transmutation.
Natural, because it just happens without help from anyone, and transmutation which means changing into something else.



Often unstable atoms will change from one kind of atom (or element) into a different kind of atom, because the number of protons changes. This is actually more like the crazy idea of a boy turning into a puppy, or a Prince into a Llama than "normal chemistry". Nuclear chem is filled with unusual events, this "simple" process of radioactive decay, or transmutation just the first of many.

The six kinds of radiation you need to know about are listed in table O. In size order from the biggest to smallest, the radiation particles are outlined in the following table.

Radiation Particle	Relative size and charge
alpha particles	mass = 4 amu charge +2
beta particles	mass = 0 these are like electrons, -1 charge the mass is zero in our class—but not "really zero"
positron particles	mass = 0 these are like +1 charged electrons, the mass is zero in our class—but not "really zero"
neutrons & protons	both having about a mass = 1 amu neutrons are neutral, protons +1
gamma radiation	no mass at all, this is just pure electromagnetic energy

As far as "strength" or penetrating power, alpha particles are hardly a match even for your skin (but don' eat them, I'm not kidding) Here is alpha, beta, and gamma radiation bumping into paper, plastic, hands, steel, and concrete. Gamma is hard to stop.

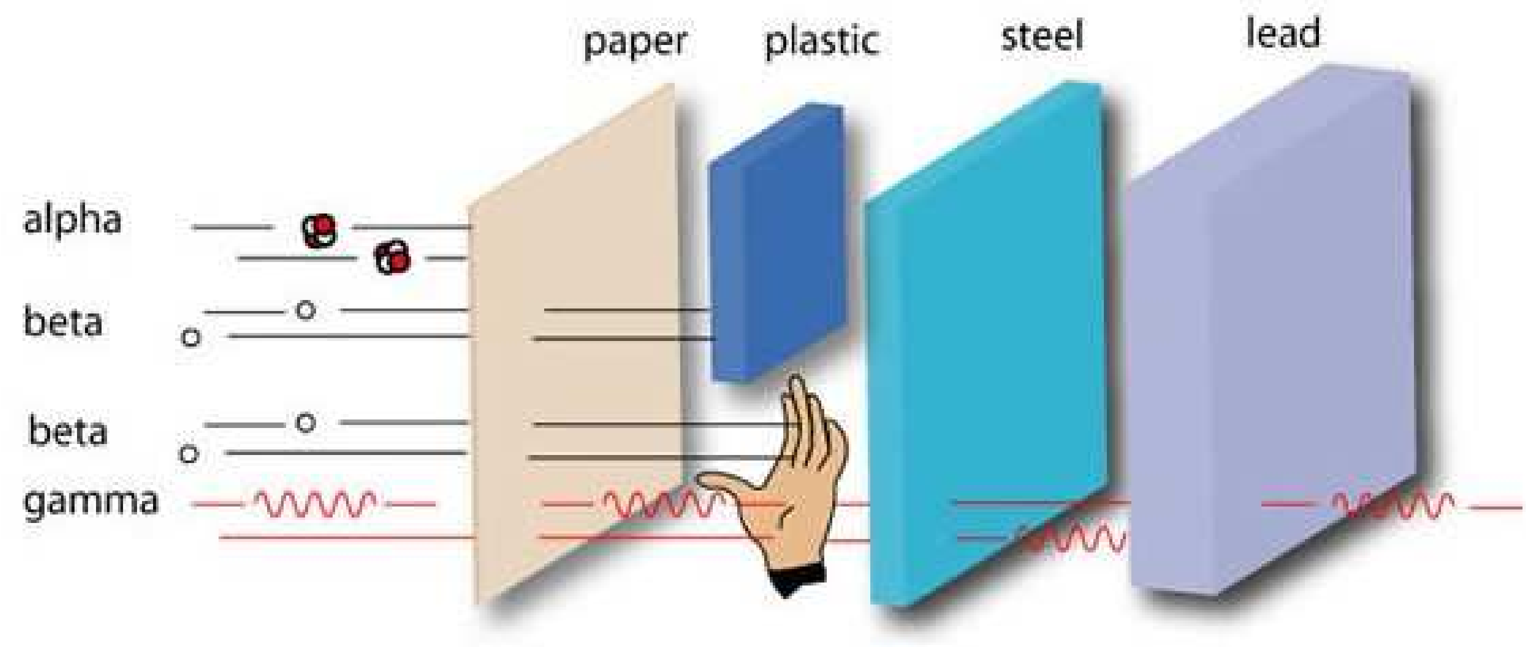


Table N: Selected Radioisotopes

The column headers on table N include nuclide (another name for radioactive isotope), half life, decay mode and nuclide name.
The first column provides you with a symbol of the radioactive isotope. The symbol is the chemical symbol from the periodic table, the number is the mass of that unstable atom. The last column just shows you how to "say" the symbol out loud.

For example, the first isotope, ^{198}Au is named gold-198. Underneath the 198 could be the atomic number, or the number of protons/electrons in gold. All gold atoms have 79 protons and 79 electrons. Not all gold is radioactive. Since the mass of this isotope is 198 and there are 79 protons, that means that this isotope has 198-79= 119 neutrons.

Another way to write this radioisotope symbol would be: $^{198}_{79}Au$

It would be sensible for the state education board to include that 79, since EVERY gold atom in the universe has 70 protons, but they are (quite literally) trying to torture a lesser grade out of you on the regents. These details matter, don't slip up!

^{14}C stands for Carbon-14, one type of radioactive carbon, the one used in carbon dating of bones and frozen mammals like mammoths. Since every carbon atom in the universe has six protons, it's written this way too: $^{12}_{6}C$

The second column on Table N is called half life. A half life is the amount of time it takes for one half the mass of a radioactive isotope to decay, or to breakdown, or change into something more stable. When an isotope decays, it quite literally emits part of its nucleus as a radioactive particle, to change the neutron proton ratio. The loss of particles leads to a more stable nucleus, which is what the isotopes is attempting to gain. Each isotope changes (or it transmutes) at its own rate. This rate is called the HALF LIFE. It is like a CLOCK, exactly half is able to change in the time called the half life. How this happens is still not explained.

Some times an isotope will decay directly into some other element and it reaches a nuclear stability in one change. More often a decay will lead to another unstable nucleus, which will also decay in a multi-step process towards obtaining a stable nucleus.

This decay is a random process, you cannot predict that "this" atom will decay and "that" one won't. Half of the atoms will decay in a half life. The length of time a half life takes is dependent upon the isotope. They all have their own rate and their own process and it takes what ever time it takes. We are given 24 half life time frames (from milliseconds to billions of years) in Table N.

The decay mode shows the individual particles of radiation that the nucleus of an isotope gives off. Some isotopes emit alpha particles, some emit beta particles, some emit the odd positron particles. Some emit gamma radiation, which is NOT even a particle, just electro-magnetic energy. All radiation is unsafe to living things. It's best to be avoiding this as the radiation can harm cells, or your whole body in bad ways.

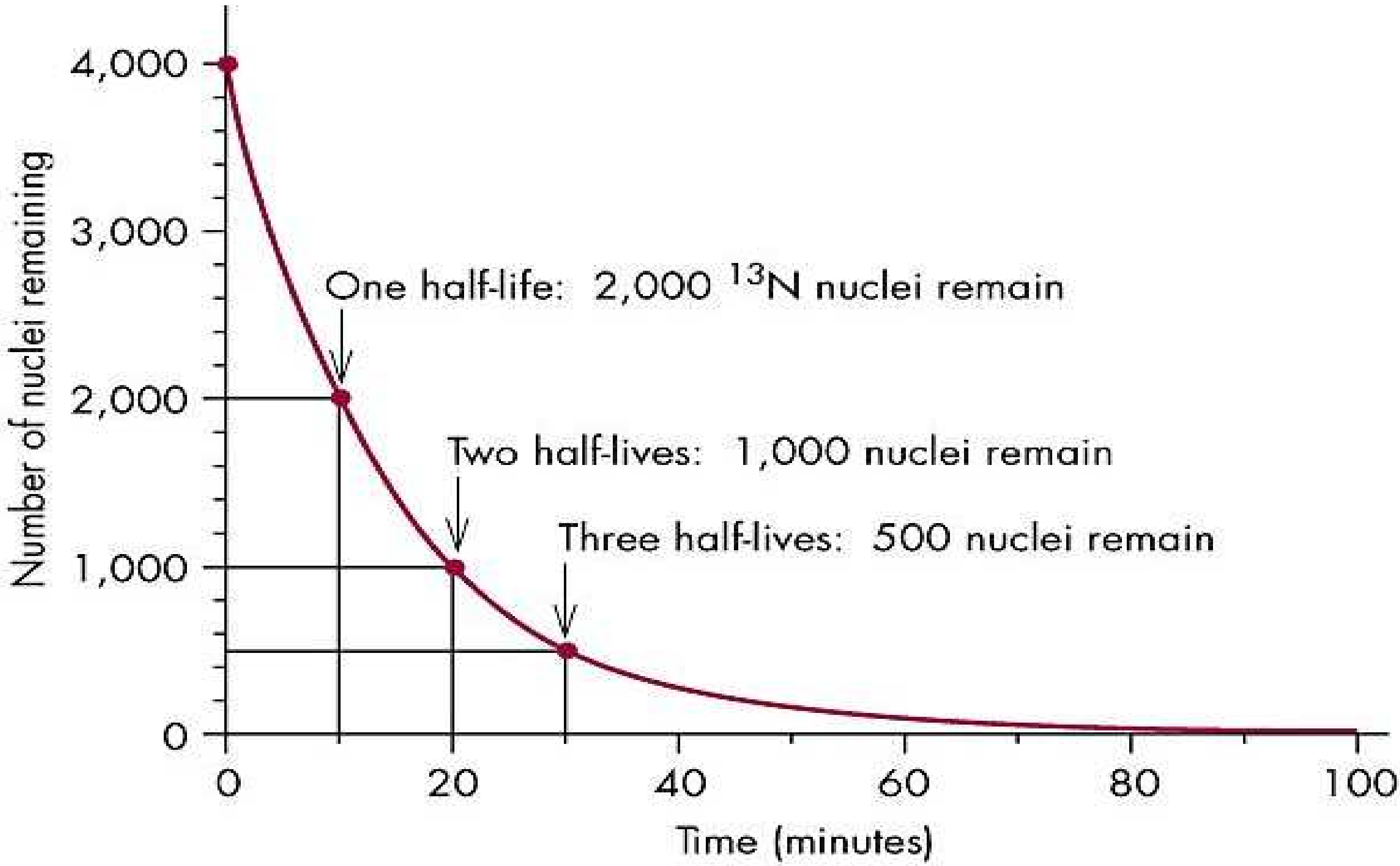
We can use the decay mode to determine what new atom the radioactive isotope will transmute into (become) when they emit or give off these radioactive decay particles.

When isotopes give off particles and transmute into new atoms, this process has several ways of being named. You could say…

- The radioisotope will decay into some other atom.
- The radioisotope will transmute into another atom.
- The radioisotope will under go natural transmutation (not caused by a scientist).
- Some isotopes undergo alpha decay, others undergo positron or beta decay.

- ***All of these statements "mean" the same thing.***

This graph shows the half life of radioactive nitrogen-13. This graph starts out at 4,000 radioisotopes and after EACH half life, there are only ONE HALF the number of isotopes left. The half life is 10 minutes.



All half life graphs are identical, the only difference being the actual time in half life. Some half lives are seconds long, some millions of years. After each half life, only half of the original isotope remains.

Below are three types of natural transmutation (all from table N). Watch how the math works - for the first transmutation, francium has 220 total neutrons and protons, when it emits an alpha particle, it emits 4 of them, and that leaves it with just 216. It starts with 87 protons, but when 2 are emitted in the alpha particle, it has just 85 left over. The only atom in the world with 85 protons is astatine. Francium transmuted into astatine. ALL DECAY MODES WORK WITH THIS SIMPLE ARITHMETIC PROCESS.

Decay Mode	radioisotope	products
alpha	${}^{220}_{87}\mathrm{Fr} \longrightarrow$	${}^{4}_{2}\mathrm{He} + {}^{216}_{85}\mathrm{At}$
beta	${}^{198}_{79}\mathrm{Au} \longrightarrow$	${}^{0}_{-1}\mathrm{e} + {}^{198}_{80}\mathrm{Hg}$
positron	${}^{19}_{10}\mathrm{Ne} \longrightarrow$	${}^{0}_{+1}\mathrm{e} + {}^{19}_{9}\mathrm{F}$

Half life examples

^{198}Au = 2.695 days ^{14}C = 5715 years ^{37}Ca = 182 milliseconds

A half life means enough time passes so that only one half of the mass of the original, unstable radioactive isotope remains. The other half of the material has transmuted into something (probably more stable, but maybe still unstable). Sometimes it is a one step process to nuclear stability, but often it takes many steps. The amount of time it takes varies greatly. The times are listed for you in Table N.

Table O decay particles and their symbols explained:

Alpha Particle: 4 is the total mass of 4 AMU. The 2 is for 2 protons included 4 AMU
(2 neutrons make up the rest of the mass)
He stands for helium, an alpha particle is identical to a He nucleus
(or a helium atom minus its electrons)

Beta Particle: 0 for no mass in high school, -1 is for a negative one charge, e for electron.
Beta particles are LIKE electrons

Gamma Radiation: no mass, no charge, pure energy and very much not healthy for humans

Neutron: 1 amu mass, no charge, n for neutron

Proton: 1 amu mass on top, +1 charge since it is a proton, H for the hydrogen nucleus which is the whole nucleus of a (non-radioactive) hydrogen atom. Less than 1% of all hydrogen on Earth is radioactive. Deuterium has 1 p^+ plus 1 n°
Tritium has 1 p^+ and 2 n° with a mass of 3 AMU.
"Normal" or non-radioactive hydrogen has no neutrons at all.

Positron Particle: 0 for no mass in high school, +1 for a positive one charge, and the e is for electron. Strange things happen in nuclear chemistry. Positron particles are very strange. They have the e like an electron, but they are positively charged, which is opposite of electrons. These are also called anti-electrons because they are the opposite of electrons. (technically they have the tiny mass of an electron)

FISSION VS. FUSION Reactions

The transmutation of radioactive isotopes into more stable isotopes occurs without any help from scientists. It occurs at it's own rate which can't be speeded up or slowed either. These are NATURAL transmutations because they occur naturally, without human intervention.

Some transmutations only occur when humans get mixed up in it. These are called artificial transmutations. They include FISSION reactions, which mean the "splitting of atoms" which occurs in many nuclear bombs and in all nuclear reactors. There are many kinds of fission reactions (like there are many compounds that could combust, or many synthesis reactions that could occur). All fission reactions have humans blasting an atom's nucleus with particles to make it unstable, and these unstable nuclei are compelled to split apart immediately.

When they split, they release 2 or more daughter nuclei (smaller atoms), extra neutrons to expand the reaction, and some energy too. This process repeats over and over, making the reaction get bigger and bigger each cycle, releasing more and more energy. With enough fuel to start with this will literally explode with crazy energy, a nuclear bomb type explosion. To explode like this, sufficient radioisotope must be present to split. If not enough is present, the reaction continues, but the explosion is much smaller.

An example of FISSION reactions follow: U-235 forms U-236 when bombed by a neutron. This splits into the 2 daughter isotopes (Kr and Ba) releasing 3 more neutrons and energy. This cycles over and over, releasing more and more energy.

$$^{235}U + n^o \rightarrow \; ^{236}U \rightarrow \; ^{92}Kr + \; ^{141}Ba + 3n^o + \text{energy}$$

In a power plant, this reaction is controlled (by the control rods) which lower into the reactor core, and absorb neutrons. This allows the chain reaction to run, but not get out of control. It keeps the fission going, but limits the rate, which allows the reactor to just stay very hot. The heat is used to produce energy to turn a turbine to make electricity.

FUSION reactions are not the same as fission, although they release even more energy. In fusion, small atoms (hydrogen usually) are squished together under extreme heat and pressure to make helium atoms. On the Sun, the process is different than on Earth. Humans have been able to make fusion happen, but in a slightly different (easier) way. The amount of energy released in fusion reactions is so great that it is uncontrollable. The Sun produces heat this way, humans make hydrogen bombs, much more powerful weapons than fission bombs.

Simplified Fusion on Earth is done this way: $^{2}H + \; ^{3}H \rightarrow \; ^{4}He + n^o + \text{energy}$

Simplified Fusion on the Sun is done this way: $4H^{+1} \rightarrow He + 2n^o + 2 \text{ positrons} + \text{energy}$

The second process requires vast pressure and heat, available in the center of the Sun but not on Earth.

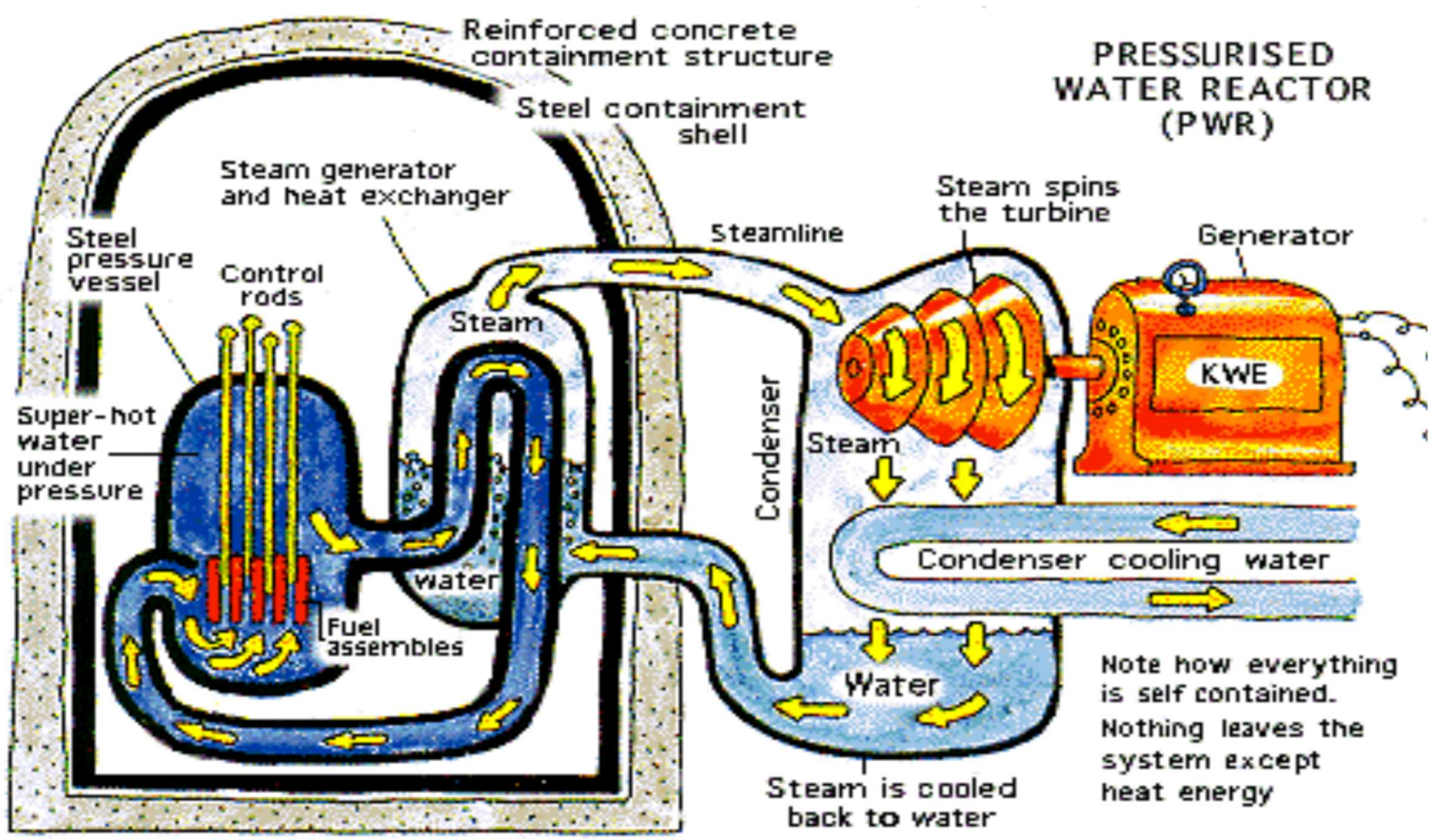
In both Fission and Fusion reactions there is a small loss of mass, which can be explained with Einstein's equation of $e=mc^2$ or energy equals matter times the speed of light squared.

What that really means is that this is WAY to complicated to really explain, but in fact, some mass of the reactants is lost, and converted into huge amounts of energy. In that equation, the "important" thing to see is that e=m, energy and mass are the SAME THING. A small bit of mass can be multiplied by a huge constant (squared) to equal energy. A little mass is equal to A LOT of energy. How this happens is not easily explained in high school, but it happens nonetheless.

A fission reaction nuclear power plant operates to produce electricity. All power plants make heat, to boil water into high pressure steam. The steam pumps through pipes, and turns the blades of a turbine (like a big propeller) to turn the magnets around wires. This moving magnetic field creates motion in electrons (electricity). That's been known for a hundred years, but it is still more complex than this few sentences makes it seem.

Burning coal, oil, or gases to make heat to do this occurs all of the time. The use of a controlled fission reaction, one that does not get out of control, is a way to make heat. The US has about 99 reactors in 61 plants (some plants have more than one reactor). As of June 2015, there are 438 nuclear power plants in 31 countries (including the US). The country of France has the most reactors under construction at this time.

Below is a cartoon diagram showing a simple version of how a plant works.



Negative points to nuclear power:

- Until a technology for safe, permanent containment of radioactive wastes has been developed and tested, it is irresponsible to continue producing them.
- Nuclear wastes remain dangerous for extremely long periods of time, no human institutions or physical buildings have lasted even close to long enough to be sure that they will remain “safe”.
- Nuclear wastes could get into our environment at any time over 240,000 years, causing unbelievable harm to life.
- Ethically, we do not have the right to burden future generations with the potential risks posed by nuclear wastes.
- The alleged "perfect" record of nuclear transport is flawed. No major accidents have occurred, but many troublesome incidents have.
- Fukushima Daiichi in Japan, and Chernobyl in Russia nuclear plants all had real disasters - meltdowns with radiation leaks and terrible results.
- The Three Mile Island Pennsylvania nuclear plant had a very near accident (almost a meltdown) in March 1979, but it was averted at the last minute.

Positive points to nuclear power:

- Finding a new way to store, or deal with wastes might be just around the corner.
- A relatively small volume of waste produced makes them easy to control and protect.
- There is no carbon dioxide produced by nuclear power, better for global warming problem
- Shipping of nuclear fuel has never been compromised in the past 20 years
- There has never been a nuclear reactor failure in the USA ever.
- The electricity price is relatively cheap (subtracting clean up costs of accidents and the problem of long term waste storage)

Nuclear Bombs dropped on Japan

At the end of World War Two, America dropped 2 atomic bombs on Japan to force it to surrender and end the war. Both bombs were fission bombs, meaning that a chain reaction was allowed to occur which lead to a near instantaneous release of enormous energy, killing many thousands of people immediately, and exposing many more thousands to high doses of radiation, which poisoned them.

The bomb dropped on Hiroshima was called “Little Boy”, on August 6, 1945. The bomb consisted of enriched uranium (concentrated radioactive isotope).
Approximately 600 milligrams of this uranium was converted into energy. About 140,000 humans were killed in total (blast and radioactive poisoning).

The bomb dropped on Nagasaki came three days later. It was called “Fat Man”, and was a plutonium bomb. This bomb exploded about 1800 feet over the city, and killed about 40,000 people instantly. Many thousands more died from radiation poisoning. This bomb was actually stronger in explosive power but due to the hilly terrain was less destructive than the bomb in Hiroshima where it was flatter.

Modern nuclear bombs are much bigger and usually are hydrogen bombs (a fission bomb is used to trigger a secondary fusion reaction). A fission bomb is a million times bigger than a regular military bomb. A fusion bomb is about 4X bigger than a fission bomb.

Dirty Bombs

A dirty bomb is not nearly as destructive as an actual nuclear bomb. A dirty bomb is a relatively small explosive device that is wrapped with radioactive material. The bomb blasts this radioactive material into the environment, causing little physical damage, but a lot of psychological fear, and causing the deaths of few people by radiation poisoning. Clean up would be difficult, expensive, and possibly impossible. This bomb is designed to cause havoc and economic damage rather than kill many people.

Carbon Dating

On Earth there is a known ratio of "normal" non-radioactive carbon C-12 and of radioactive carbon C-14. This ratio is a constant on the whole planet and is checked from time to time. Since this ratio is constant, all living things take in carbon (plants take in carbon dioxide, animals eat plants, or other animals that ate plants), and all living things have this same ratio of C-12 to C-14 in their bodies as is found in nature. The half life of radioactive carbon is also known (about 5730 years according to our reference tables).

When we are alive we consume carbon in the ratio that it exists. When we die we stop absorbing carbon (C-12 and C-14). The C-14 continues to decay and over time the ratio between C-12 and C-14 changes, because we are not replacing the decayed carbon anymore because we stopped eating when we died.

Using some fancy math, and good tools, the change in the ratio between the carbons can be measured, and mathematically it can be determined how long ago the "fossil" stopped eating, or how long ago it died, or, how old it is.

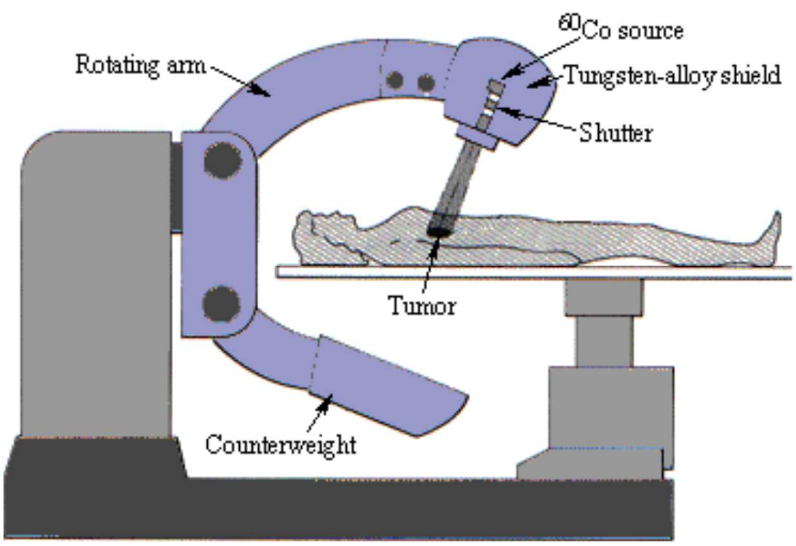
This will work for organic material up to about 70,000 years or so. Older material has so little radioactive carbon left that the errors inherent in measuring the amount exceed the precision of the measurement. Thus, this can be used to date old stuff, but not nearly old enough to date dinosaur fossils or the Earth itself. For that we use the changing ratios of other, longer half life radioisotopes.

This is a simple explanation, of a relatively simple process, but this is not something that we can do in lab tomorrow. It is commonplace and very well accepted to work accurately to about 70,000 years.

Medical uses for radioactive materials

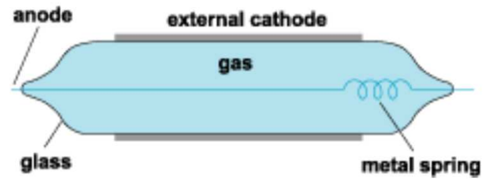
Doctors can use radioactive cobalt-60 to produce beams of beta particle radiation which can be carefully aimed at tumors and cancers that cannot be operated on because of their locations. The radiation kills most of the cells it hits, including the healthy ones that are not cancer. The general plan is to kill all of the bad cancer cells, and as few of the good ones as possible. Once the tumor or cancer is treated or destroyed, the body will hopefully be able to repair most of what was damaged by the treatments. The net result is better than letting the tumor kill a person, but radiation is not good for living cells, this treatment works but the side effects are not to be taken lightly.

Doctors can also use radioactive iodine-131 to inject into people, to diagnose how the thyroid gland is absorbing iodine. After a period of time a radiograph (type of x-ray picture) can be taken of the neck where the thyroid is, and doctors can measure how much of the radioactive iodine was absorbed and compare that to "normal" uptake. Radiation is always bad, but here a small amount is injected to a person and the results "are worth more" than the expected negative effects.



Geiger Counters

These are devices that measure the presence and concentration of radioactive particles. Developed by Hans Geiger and others. The cylinder of gas is affected by the particles, and these radioactive particles ionize some of the gas.



These ionized gas particles ionize others, and the amount of particles is measured electrically along a high voltage wire in the tube. The more particles ionized, the greater amount of radioactivity is present.

Often these devices will count the amount of energy by audible clicks that can be heard by the person with the Geiger counter in hand. The more clicks, the greater radioactivity. (run!)

A modern Geiger Counter is at left, and the way the device works is shown in blue. The gas atoms are ionized and “counted” by the high voltage wire strung through the center.

Measuring Radiation exposure in humans:

Radiation is usually measured in millirems. Americans are usually are exposed to 300 millirems of naturally occurring radiation in a year and about 60 more millirems of man-caused radiation (smoking, smoke detectors, fallout from nuclear tests of the past, X-rays, color televisions, cell phones, and nuclear power plant leakages, etc.).

Measuring the amount of radiation you are exposed to can be done electronically, or with old fashioned “film” badges which get developed and checked for “darkness” or exposure to radiation. Federal and state governments set standards for allowable exposure to radiation. Workers in health fields (dentist, doctor, X-ray technicians, etc.) all are monitored and limited to certain exposures per day, week, or year. If people are accidentally over exposed, they are not permitted to work until a period of time passes.

If you are overexposed to radiation you may die. You may develop cancer, and you may get sick in the short term. Different radiations and different levels of exposure will produce various effects. Radiation sickness is describe as: Illness induced by exposure to ionizing radiation, ranging in severity from nausea, vomiting, headache, and diarrhea to loss of hair and teeth, reduction in red and white blood cell counts, extensive hemorrhaging, sterility, and death.