Nuclear Reactions

We discussed the use of the Periodic Table of Elements that shows how the various atoms vary as the balanced positive and negative charges in atoms increase beyond hydrogen. In nuclear physics, a different chart, the **Chart of Nuclides**, helps us organize our understanding of nuclear physics and radioactivity. A small, but complete version of it is at *https://yosemitefoothills.com/Science-1A/Chapter_13-NuclearReactions/ChartOfNuclides.png*
This version has been chopped and rearranged to use the chart space more efficiently. The middle band shows n=0 to n=69, the upper-right band continues to n=139, and the remaining nuclei are presented in the lower-left band.

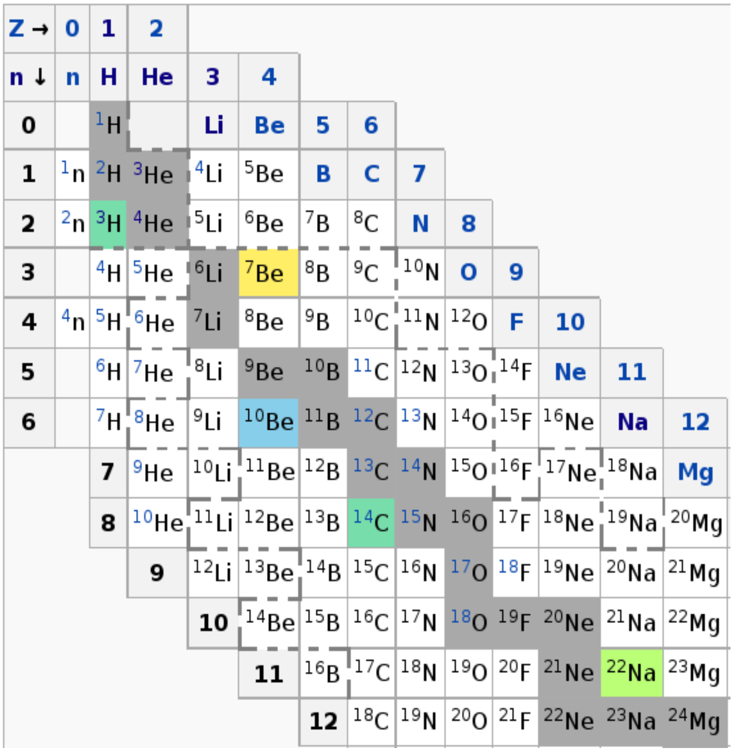
A full-size, colored version can be seen on Wikipedia at *http://en.wikipedia.org/wiki/Table_of_nuclides*
which actually goes a bit beyond Z=106.

The image at the right is a blown-up view of the upper-left portion of that chart. It will be useful for illustrating the main features of the Chart of Nuclides.

At the very top, is "Z→" to show that the proton count Z of the various nuclei (which equals the atomic number of the corresponding atoms) increases as one progresses toward the right in this chart. Similarly, at the left is "n ↓" to show that the neutron count n of the various nuclei increases as one progresses toward the bottom in this chart.

The chemical symbol for the atoms that correspond to each Z value is shown below the Z value. All the nuclei in a single column are said to be different **isotopes** of the atom nucleus listed at the top of the column. They have the same number of protons, but different numbers of neutrons.

Nuclei in squares with a dark gray background are **stable**, they do not spontaneously change into another nucleus. Those with a white background are highly **unstable** and decay in less than a day. Intermediate shades indicate varying degrees of stability from a day to millions of years.



Z →	0	1	2										
n ↓	n	H	He	3	4								
0		^{1}H		Li	Be	5	6						
1	^{1}n	^{2}H	^{3}He	^{4}Li	^{5}Be	B	C	7					
2	^{2}n	^{3}H	^{4}He	^{5}Li	^{6}Be	^{7}B	^{8}C	N	8				
3		^{4}H	^{5}He	^{6}Li	^{7}Be	^{8}B	^{9}C	^{10}N	O	9			
4	^{4}n	^{5}H	^{6}He	^{7}Li	^{8}Be	^{9}B	^{10}C	^{11}N	^{12}O	F	10		
5		^{6}H	^{7}He	^{8}Li	^{9}Be	^{10}B	^{11}C	^{12}N	^{13}O	^{14}F	Ne	11	
6		^{7}H	^{8}He	^{9}Li	^{10}Be	^{11}B	^{12}C	^{13}N	^{14}O	^{15}F	^{16}Ne	Na	12
		7	^{9}He	^{10}Li	^{11}Be	^{12}B	^{13}C	^{14}N	^{15}O	^{16}F	^{17}Ne	^{18}Na	Mg
		8	^{10}He	^{11}Li	^{12}Be	^{13}B	^{14}C	^{15}N	^{16}O	^{17}F	^{18}Ne	^{19}Na	^{20}Mg
			9	^{12}Li	^{13}Be	^{14}B	^{15}C	^{16}N	^{17}O	^{18}F	^{19}Ne	^{20}Na	^{21}Mg
				10	^{14}Be	^{15}B	^{16}C	^{17}N	^{18}O	^{19}F	^{20}Ne	^{21}Na	^{22}Mg
					11	^{16}B	^{17}C	^{18}N	^{19}O	^{20}F	^{21}Ne	^{22}Na	^{23}Mg
						12	^{18}C	^{19}N	^{20}O	^{21}F	^{22}Ne	^{23}Na	^{24}Mg

Ordinary hydrogen, has a single proton and no neutrons in its nucleus. It is found at Z=1 and n=0 where the symbol ^{1}H is placed. There is, however, another hydrogen entry ^{2}H at Z=1 and n=1 which is also shaded dark gray to indicate that it too is stable. 0.015% of hydrogen in ocean water is this rare, heavy version of hydrogen called **deuterium**.

Below ^{2}H, in a lighter shade of gray (green in the colored image) is ^{3}H which is not stable. It spontaneously decays by emitting an electron (**beta decay**) and becomes ^{3}He, an uncommon, but stable, form of helium. ^{3}H is called **tritium**. When tritium changes to ^{3}He, one of its two neutrons changes into a proton while shooting out an electron. Half of a container of tritium will have changed into ^{3}He after about 12 years, a time interval is called its **half-life**.

Below ^{3}He, is found ^{4}He. It is ordinary helium with Z=2 and n=2. Both ^{3}He and ^{4}He are stable.

The far left column has a lone neutron ^{1}n with Z=0 and n=1. A neutron that is by itself (not part of a larger nucleus) is unstable and beta decays with a half-life of 15 minutes into a proton (^{1}H), an electron, and a massless particle called an anti-neutrino. Because it has no charge, an isolated neutron cannot be the nucleus of an atom.

Carbon at Z=6 has two stable isotopes, ^{12}C which is 98.9% of the carbon around us and ^{13}C which is about 1%. It also has a famous radioactive isotope ^{14}C which is created indirectly by cosmic rays in the atmosphere and comprises only 1 out of 10^{12} carbon nuclei in the atmosphere and in living organisms. ^{14}C beta decays into ^{14}N with a half life of 5730±40 years.

While living, an animal or plant maintains the same concentration of ^{14}C in its carbon atoms as is in the atmosphere, but when it dies (stops eating or growing), the ^{14}C decays without being replenished. This fact allows the ratio of ^{14}C to ^{12}C to be used for determining how long ago an organism was last living and is called **carbon dating**.

About 18% of our body mass is carbon. For a person that weighs 67 kg, this corresponds to about 12 kg of carbon. Those 12 kg contain about 6×10^{26} atoms, of which 6×10^{14} are ^{14}C. Of those about 3000 are beta-decaying to ^{14}N every second. Also, about 0.01% of the potassium in our bodies is radioactive with a half-life of a billion years, but there is so much that it too provides about 6000 decays per second. We are unavoidably radioactive.

Notice how in the Chart of Nuclides a beta-decay transforms a nucleus from its original block to one that is one block higher and one block to the right. Also note how the stable nuclei tend to lie on or below the line where Z=n (^{1}H and ^{3}He are exceptions). As Z becomes larger, nuclei tend to require more neutrons than protons to be stable; they fall below the Z=n line of blocks.

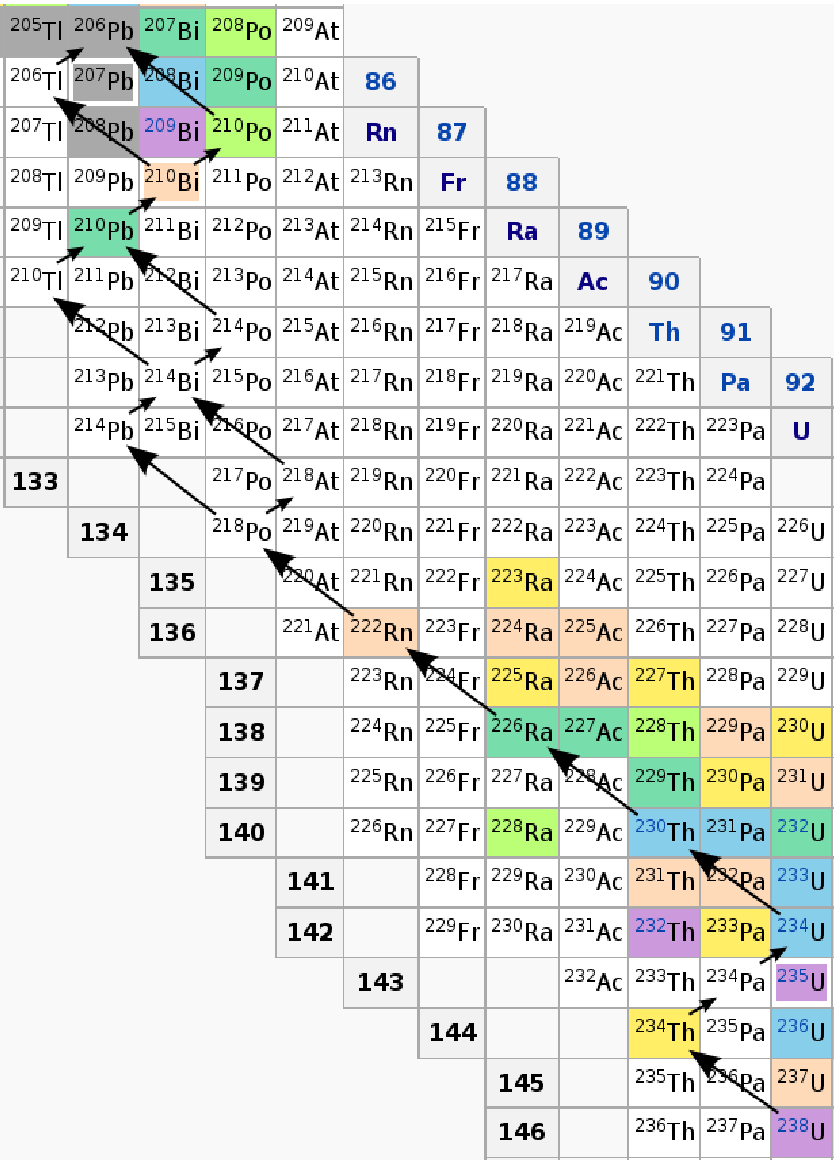
With a few exceptions, there are stable nuclei up to lead (Pb) at Z=82. No nuclei are completely stable at higher Z although some have very long half-lives such as $^{209}_{83}\text{Bi}_{126}$ that has a half-life of $2\times10^{19}\text{ years}$, more than a billion times the age of the universe!

Another interesting case is that of ^{238}U at Z=92 and n=146 which is identified in the text as $^{238}_{92}\text{U}_{146}$. Its eventual decay into $^{206}_{82}\text{Pb}_{124}$ is shown in the figure to the right. (Figure 13.17 on page 320 of the text shows the same information using different coordinates.)

The decay of $^{238}_{92}\text{U}_{146}$ proceeds in steps, passing through a number of unstable nuclei until it finally stops at $^{206}_{82}\text{Pb}_{124}$, the first stable nucleus it reaches. The longer arrows pointing to the upper left indicate that a nucleus undergoes an **alpha decay**, it spits out a bundle of 2 protons and 2 neutrons called an **alpha particle** (which is identical to a helium nucleus $^{4}_{2}\text{He}_{2}$). The short arrows pointing to the upper right indicate that the nucleus undergoes a beta decay similar to that which converts tritium to $^{3}_{2}\text{He}_{1}$. The electron that is emitted is called a **beta particle**. You can see that there are some alternate paths in this decay chain. Half-lives are a statistical concept and which path is followed is a matter of chance.

Within the decay chain of $^{238}_{92}\text{U}_{146}$ are the radioactive isotopes radium $^{226}_{88}\text{Ra}_{138}$ and radon $^{222}_{86}\text{Rn}_{136}$. Radium used to be used for providing lighted watch dials. A tragic story about this is described at *https://en.wikipedia.org/wiki/Radium_Girls* .

Radon is commonly found in cellars since it is a heavy inert gas. As a gas, it can be inhaled and turns out to be the greatest source of natural radioactivity affecting humans.



^{205}Tl	^{206}Pb	^{207}Bi	^{208}Po	^{209}At							
^{206}Tl	^{207}Pb	^{208}Bi	^{209}Po	^{210}At	**86**						
^{207}Tl	^{208}Pb	^{209}Bi	^{210}Po	^{211}At	**Rn**	**87**					
^{208}Tl	^{209}Pb	^{210}Bi	^{211}Po	^{212}At	^{213}Rn	**Fr**	**88**				
^{209}Tl	^{210}Pb	^{211}Bi	^{212}Po	^{213}At	^{214}Rn	^{215}Fr	**Ra**	**89**			
^{210}Tl	^{211}Pb	^{212}Bi	^{213}Po	^{214}At	^{215}Rn	^{216}Fr	^{217}Ra	**Ac**	**90**		
	^{212}Pb	^{213}Bi	^{214}Po	^{215}At	^{216}Rn	^{217}Fr	^{218}Ra	^{219}Ac	**Th**	**91**	
	^{213}Pb	^{214}Bi	^{215}Po	^{216}At	^{217}Rn	^{218}Fr	^{219}Ra	^{220}Ac	^{221}Th	**Pa**	**92**
	^{214}Pb	^{215}Bi	^{216}Po	^{217}At	^{218}Rn	^{219}Fr	^{220}Ra	^{221}Ac	^{222}Th	^{223}Pa	**U**
133			^{217}Po	^{218}At	^{219}Rn	^{220}Fr	^{221}Ra	^{222}Ac	^{223}Th	^{224}Pa	
	134		^{218}Po	^{219}At	^{220}Rn	^{221}Fr	^{222}Ra	^{223}Ac	^{224}Th	^{225}Pa	^{226}U
		135		^{220}At	^{221}Rn	^{222}Fr	^{223}Ra	^{224}Ac	^{225}Th	^{226}Pa	^{227}U
		136		^{221}At	^{222}Rn	^{223}Fr	^{224}Ra	^{225}Ac	^{226}Th	^{227}Pa	^{228}U
			137		^{223}Rn	^{224}Fr	^{225}Ra	^{226}Ac	^{227}Th	^{228}Pa	^{229}U
			138		^{224}Rn	^{225}Fr	^{226}Ra	^{227}Ac	^{228}Th	^{229}Pa	^{230}U
			139		^{225}Rn	^{226}Fr	^{227}Ra	^{228}Ac	^{229}Th	^{230}Pa	^{231}U
			140		^{226}Rn	^{227}Fr	^{228}Ra	^{229}Ac	^{230}Th	^{231}Pa	^{232}U
				141		^{228}Fr	^{229}Ra	^{230}Ac	^{231}Th	^{232}Pa	^{233}U
				142		^{229}Fr	^{230}Ra	^{231}Ac	^{232}Th	^{233}Pa	^{234}U
					143			^{232}Ac	^{233}Th	^{234}Pa	^{235}U
						144			^{234}Th	^{235}Pa	^{236}U
							145		^{235}Th	^{236}Pa	^{237}U
							146		^{236}Th	^{237}Pa	^{238}U

Sometimes, a nucleus might end up with too many protons. It can either capture a nearby electron (**electron capture**) and convert one of its protons to a neutron or it can directly change a proton to a neutron by emitting a **positron**, an electron-like particle with a positive charge. This latter process is called **positron emission**.

Certain nuclei are so unstable that, when struck by a neutron, they break apart (**nuclear fission**) into two large, unequal chunks (called **daughter nuclei**) and some small debris. $^{235}_{92}\mathrm{U}_{143}$ is such a nucleus. Among its daughter nuclei (or their decay products) are the biologically dangerous radioactive elements $^{131}_{53}\mathrm{I}_{78}$ (half-life 8 days), $^{90}_{38}\mathrm{Sr}_{52}$ (half-life 29 years) and $^{137}_{55}\mathrm{Cs}_{82}$ (half-life 30 years). When $^{131}_{53}\mathrm{I}_{78}$ is ingested, it becomes concentrated in the thyroid gland where it can cause cancer. $^{90}_{38}\mathrm{Sr}_{52}$ is dangerous because it is chemically similar (same column in the Periodic Table) to calcium Ca which is the main constituent of our bones where new blood cells are created. It is known to cause bone cancer and leukemia. Similarly, $^{137}_{55}\mathrm{Cs}_{82}$ is chemically similar to potassium K which is 0.03% of the atoms in humans. Potassium is involved in our neural functions and the maintenance of cellular electrolyte balance.

Nuclei that fission are used for atomic bombs (better called nuclear fission bombs). The key to their chain reaction is that when an extra neutron hits a $^{235}_{92}\mathrm{U}_{143}$ nucleus, the nucleus quickly breaks apart producing daughter nuclei plus two or more additional neutrons. Those additional neutrons then cause other $^{235}_{92}\mathrm{U}_{143}$ nuclei to fission leading to a violent chain reaction. Each fission releases over a million times more energy than a chemical reaction. This was beautifully illustrated using mousetraps in the Disney movie "Our Friend the Atom".

Nuclear fission reactors use neutron absorbing materials to allow a nuclear reaction to proceed gradually without an explosion. They can then heat water and operate electric generators with steam.

The interior of the earth is liquid because of heat liberated by nuclear fission of uranium and other radioactive elements within it.

Nuclei also emit extremely high energy photons called gamma rays. Just as atoms emit or absorb visible and X-ray photons when they adjust their electron clouds, nuclei can emit gamma ray photons when they make internal adjustments to their protons and neutrons after being created by a nuclear decay.

Beta rays are stopped by a few sheets of paper or our skin. Nuclei that emit them are therefore not particularly dangerous unless they are ingested with food or are present as a gas in the air we breath. The unavoidable 3000 $^{14}\mathrm{C}$ nuclei in our bodies that decay each second along with other natural radiation causes some of our cancers as the radiation damages DNA.

Alpha particles are much more energetic and can cause more damage than beta rays, but they are also easily stopped by our skin. If ingested, however, atoms that emit alpha rays can do much more damage than beta rays.

Gamma ray photons can easily penetrate matter and cause damage by disrupting chemical bonds; skin and clothing does not protect against gamma rays. Our bodies are nearly transparent to extremely high energy gamma rays found in cosmic rays, but there is a range of gamma ray energies that can cause considerable biological damage, greater than, but otherwise similar to X-ray damage.

In spite of all this biological danger, the land for a radius of 30 km around the Chernobyl nuclear disaster of 1986, while abandoned by humans, has become a wildlife sanctuary with little sign of radiation effects on its expanding populations of wolves, moose and beaver.

Einstein's famous $E=mc^2$ equation that connects mass with energy using the square of the speed of light is nicely illustrated by precise measurements of nuclear masses. For example, the $^{4}\mathrm{He}$ nucleus is composed of two protons with a mass of 1.00727646677 amu each and two neutrons with a mass of 1.0086649156 amu each. The masses of its protons and neutrons add up to 4.02910586708 amu, but the actual mass of a $^{4}_{2}\mathrm{He}_{2}$ nucleus is 4.001506179127 amu, 0.02759968795 amu smaller! The nuclear forces holding the $^{4}_{2}\mathrm{He}_{2}$ nucleus together reduce its energy, and because energy and mass are related by Einstein's equation, the measured mass is reduced by this binding energy divided by the square of the speed of light. The $^{4}_{2}\mathrm{He}_{2}$ nucleus therefore has less energy than its parts.

There is also a mass reduction caused by the chemical binding energy that holds atoms together, but in that case it is too small to measure directly. It is the release of enormous nuclear binding energy that makes nuclear bombs so much more powerful than chemical explosives.

$^{56}_{26}\mathrm{Fe}_{30}$ is the most tightly bound nucleus. Nuclear energy is released when radioactive nuclei heavier than it decay to smaller masses and also when nuclei lighter than it are assembled into larger masses.
It is this binding energy referred to as the **nuclear glue** (caused by a **strong nuclear force**) that can overcome the

repulsive energy of the collection of positively-charged protons in a nucleus. Both protons and neutrons contribute to this binding energy, but this nuclear glue only acts over very short ranges and cannot act across the diameter of a larger nucleus. It is for that reason that larger nuclei need more neutrons than protons; the neutrons provide nuclear glue without contributing to the repulsive electric forces.

Nuclear energy is not only released when uranium breaks apart (**nuclear fission**). It is also released when ${}^{4}_{2}\mathrm{He}_{2}$ is assembled (**nuclear fusion**). When the sun or a hydrogen bomb generates energy, smaller nuclei are being assembled into larger nuclei. Efforts to generate electricity by controlled nuclear fusion have been underway for the past 50 years, but success seems to always be just about 10 years away.