Nuclear Stability

A major concept to remember: "Nature seeks the lowest energy state". In the lowest energy state, things are most stable…less likely to change. The following information that talks about stability is all based on the nucleus tending towards the lowest energy state. Stable atoms have low energy states.

All nuclei are composed of two basic particles, neutrons and protons. Neutrons and protons are almost the same size but differ in their electrical charge. Neutrons have no electrical charge and contribute only mass to the nucleus. Each proton has a positive charge equal in strength to the negative charge carried by an electron.

The number of protons in a nucleus is the atomic number (Z) and establishes the chemical identity of the atom. Each atomic number corresponds to a different chemical element; there are now approximately 106 known chemical elements that correspond to nuclei containing from 1 to 106 protons.

Because of their very small size it is not convenient to express the mass of nuclei and atomic particles in the conventional unit of kilograms. A more appropriate unit is the atomic mass unit (amu), the reference for which is a carbon atom with a mass number of 12, which is assigned a mass of 12.000 amu. The relationship between the atomic mass unit and kilogram is

1 amu = 1.66 x 10-27 kg.

The difference in mass between a neutron and proton is quite small: approximately 0.1 %. The larger difference is between the mass of these two particles and the mass of an electron. More than 1,800 electrons are required to equal the mass of a proton or neutron.

The total number of particles (neutrons and protons) in a nucleus is the mass number (A, would have been nice if it were called nucleon number). Since neutrons and protons have approximately the same mass, the total mass or weight of a nucleus is, within certain limits, proportional to the mass number. However, the nuclear mass is not precisely proportional to the mass number because neutrons and protons do not have the same mass, and some of the mass is converted into energy when the nucleus is formed ($E=MC^2$). The relationship between mass and energy is considered in more detail later.

There is a standard method for labeling different nuclear compositions: The mass number is designated by either a superscript preceding the chemical symbol, such as ^{14}C or ^{131}I, or by a number following the symbol, such as C-14, I-131, etc. The atomic number is added as a subscript preceding the chemical symbol. Adding the atomic number to the symbol is somewhat redundant since only one atomic number is associated with each chemical symbol or element.

With the exception of the most common isotope of hydrogen, all nuclei contain neutrons and protons. The lighter elements (with low atomic and mass numbers) contain almost equal numbers of neutrons and protons. As the size of the nucleus is increased, the ratio of neutrons to protons increases to a maximum of about 1.3 neutrons per proton for materials with very high atomic numbers. The number of neutrons in a specific nucleus can be obtained by subtracting the atomic number from the mass number. One chemical element may have nuclei containing different numbers of neutrons. This variation in neutron composition usually determines if a nucleus is radioactive.

Nuclear stability refers to the tendency of a nucleus of an atom to decay, which means to change into something else. If the isotope of an element (called a nuclide) is unstable (not stable), the nuclide has the tendency of emitting some kind of radiation, and is called radioactive. Radioactivity is associated with unstable nuclides. Carbon-12 is a carbon atom with a total atomic mass of 12. Since carbon can only have 6 protons, carbon-12 must have 6 neutrons (mass of 12 – 6 = 6). Carbon-12 is stable. Carbon-14 is unstable and has 8 neutrons (mass of 14 – 6 = 8).

Stable nucleus – non-radioactive
Unstable nucleus – radioactive
Also-- less stable means more radioactive and more stable means less radioactive.

What makes a nucleus stable?

The major underlying reason is: "Nature seeks the lowest energy state". In the lowest energy state, things are most stable…less likely to change. One way to view this is that energy makes things happen. If an atom is at its lowest energy state, it has no energy to spare to make a change occur. Think of yourself when you are tired and ready for sleep. In this case you will most likely just stay put and not do anything. The following information that talks about stability is all based on the nucleus tending towards the lowest energy state. Stable atoms have low energy *states. Unstable atoms will try and become stable by getting to a lower energy state. They will typically do this by emitting some form of radioactivity and change in the process. The three main forms of radioactive changes are named after the first three Greek letters: alpha, beta and gamma…more about these later.*

Science still does not completely understand why certain isotopes are more stable than others. There are some new(ish) theories, and many general observations based on the available stable isotopes. The most important concept, as was stated earlier, that governs stability is that the most stable state is the one with the lowest energy. The nucleus of a given isotope (called a nuclide) will do various things to get to the stable state.

You might wonder what forces are working in the nucleus to hold or not hold the protons and neutrons together. There are *THREE*. The positive charges of the protons tend to force the protons apart. This is called the *electromagnetic force*. There is a more mysterious force called the "*strong force*" that attracts the protons to each other. This counters the electromagnetic force. There is also another mysterious force called the "*weak force*" that governs how an unstable nucleus will decay into a stable nucleus.

THERE ARE SOME OBSERVATIONS THAT HAVE BEEN MADE TO HELP US MAKE PREDICTIONS ON WHAT NUCLIDES WILL BE UNSTABLE

science is at its best when it can correctly make difficult predictions

Neutron to proton ratio
The ratio of neutrons to protons (n/p) is a successful way in predicting nuclear stability. This ratio is close to 1 for atoms of elements with low atomic numbers (of less than about 20 protons). The n/p ratio steadily increases as the atomic number increases past element 20 (calcium) to about element 84 (polonium). Every element beyond an atomic number of 84 is unstable.

The strong nuclear force exerts an attractive force among nucleons. The more protons packed together, the more neutrons are needed to bind the nucleus together. Atomic nuclei with atomic numbers up to 20 have almost equal number of protons and neutrons. Nuclei with higher atomic numbers have more neutrons to protons. The number of neutrons needed to create a stable nucleus increases more than the number of protons. Then how do we predict the nuclear stability? One of the simplest ways of predicting the nuclear stability is based on whether a nucleus contains an odd/even number of protons and neutrons:

Protons	Neutrons	Number of Stable Nuclides	Stability

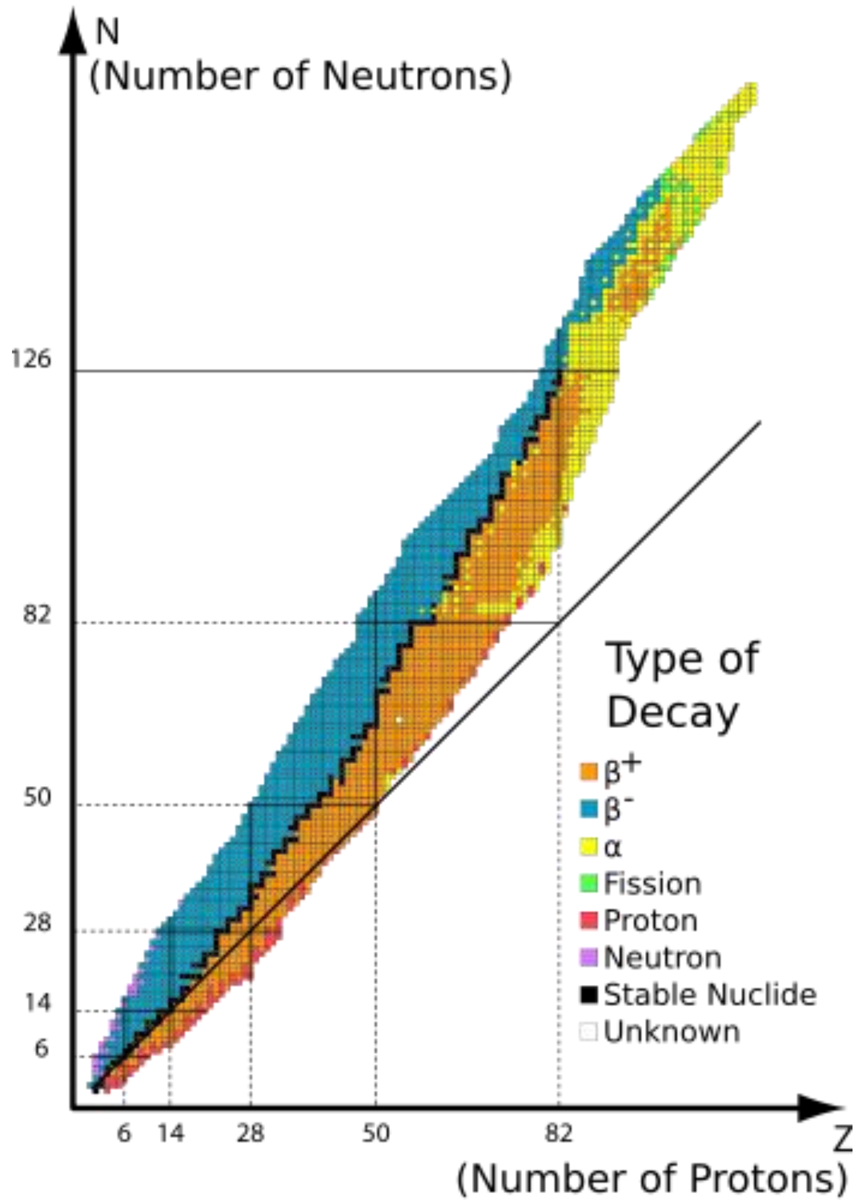
Odd	Odd	4	least stable
Odd	Even	50	more stable
Even	Odd	57	even more stable
Even	Even	168	most stable

Stability

• Nuclides containing odd numbers of both protons and neutrons are the least stable and this means more radioactive.

• Nuclides containing even numbers of both protons and neutrons are most stable and this means less radioactive.

• Nuclides contain odd numbers of protons and even numbers of neutrons are less stable than nuclides containing even numbers of protons and odd numbers of neutrons.
In general, nuclear stability is greater for nuclides containing even numbers of protons and neutrons or both.



This is a diagram of what is sometimes called the “belt of stability” or “line of stability”. The black jagged line is the most stable region. The straight black line is where proton numbers equal neutron numbers. For the first 20 or so nuclides, the jagged line is very close to the straight line. As nuclides get larger they need more neurons than protons to remain stable, so the jagged line starts getting steeper than the straight line.

Nuclei above the belt of stability can lower their ratio and move to the belt of stability by radioactive decay, which converts a neutron to a proton. This increases the number of protons and decreases neutrons and gets the nuclide on the jagged line. The opposite also can happen when the nuclide has too many protons. In this sort of decay, protons are converted to neutrons.

Other observations for prediction

- Nuclei with 2,8,20,28,50, or 82 protons; or 2,8,20,28,50,82, or 126 neutrons; are generally more stable...magic numbers.

- Nuclei with an even number of protons or neutrons are more stable than those with odd numbers.

These stability factors have been compared to the stability of 2,8,18,32 in electron shells.

Nuclear Binding Energies

Scientists discovered in the 1930's that the masses of nuclei combined are always less than these nucleons (protons and neutrons are nucleons) individually.
Mass of 2 protons = 2(1.00728 amu)
Mass of 2 neutrons = 2(1.00867 amu)
Total mass = 4.03190 amu

The mass of a Helium-4 nucleus is 4.00150 causing a mass defect (apparent loss of mass) of 0.0304 amu (4.03190 – 4.00150).
The origin of this mass defect is that some of the mass is converted to binding energy, which binds the nucleons together in the nucleus. Energy then needs to be added to separate these nucleons to overcome this binding energy. This energy, added to break the nucleons apart, is called nuclear binding energy.

Nuclear Fission

Splitting of heavy nuclei to create energy. Uses: warfare, nuclear power plants.
Problem: radioactive elements are used.

Nuclear Fusion

Combining of nuclei also release energy.
Uses: possible alternative energy source that can fuse light, nonradioactive nuclei to obtain energy.
Problem: The reaction needs high temperatures to overcome the repulsion between nuclei. The lowest temperature found to fuse deuterium with tritium is 40,000,000 K.

Example

Based on the even-odd rule presented above, predict which one would you expect to be radioactive in each of the following pairs:

a) O-16 or O-17
b) Cl-35 or Cl-36
c) Ne-20 or Ne-17
d) Ca-40 or Ca-45

Answers

(a) The $_{16}O_8$ contains 8 protons and 8 neutrons (even-even) and the $_{17}O_8$ contains 8 protons and 9 neutrons (even-odd). Therefore, $_{17}O_8$ is radioactive.
(b) The $_{35}Cl_{17}$ has 17 protons and 18 neutrons (odd-even) and the $_{36}Cl_{17}$ has 17 protons and 19 neutrons (odd-odd). Hence, $_{36}Cl_{17}$ is radioactive.
(c) The $_{20}Ne_{10}$ contains 10 protons and 10 neutrons (even-even) and the $_{17}Ne_{10}$ contains 10 protons and 7 neutrons (even-odd). Therefore, $_{17}Ne_{10}$ is radioactive.
(d) The $_{40}Ca_{20}$ has even-even situation and $_{45}Ca_{20}$ has even-odd situation. Thus, $_{45}Ca_{20}$ is radioactive.