4 Nuclear Stability And Instability

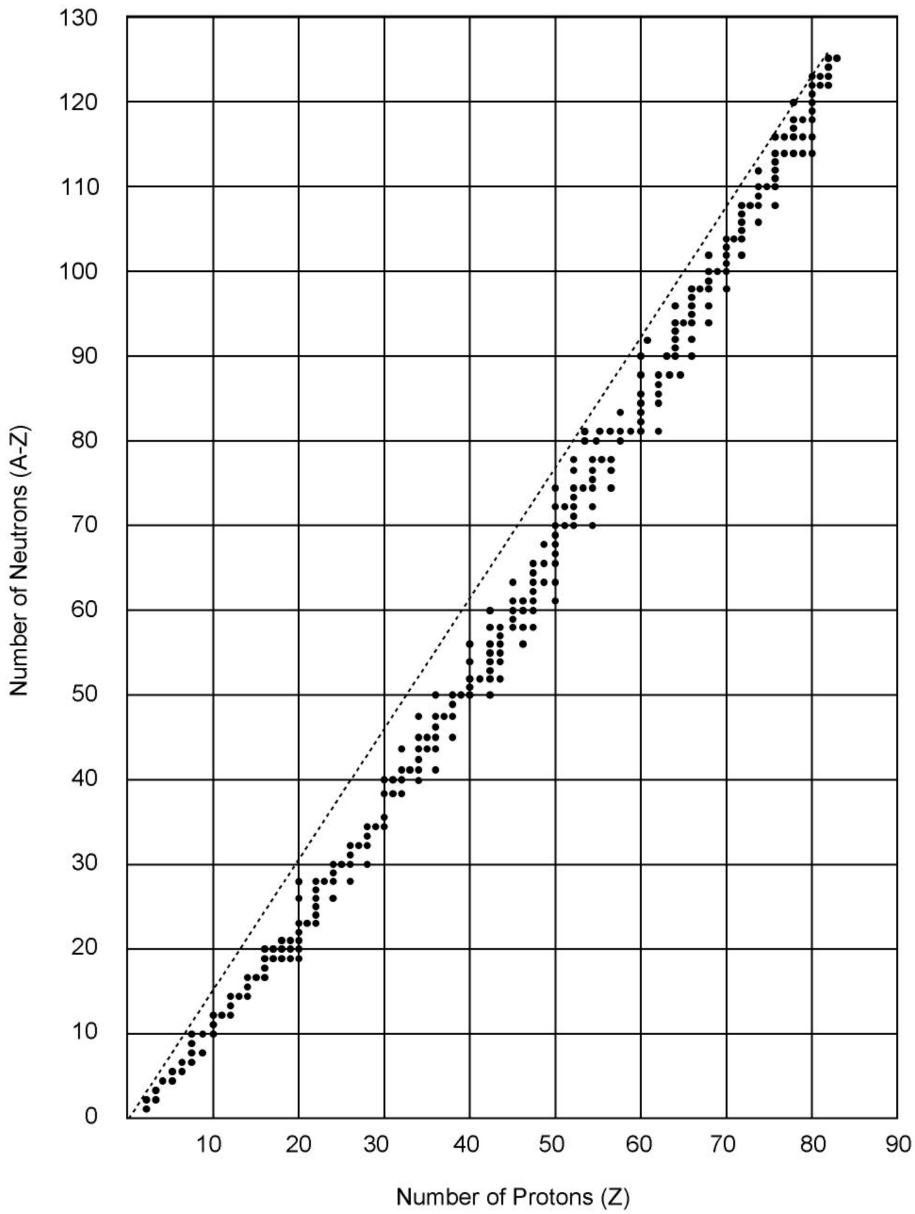

Figure 4.1
Plot of N vs. Z

Each black dot in Figure 4.1 represents a stable nuclide. Where more than one dot appears for a particular atomic number, those dots represent stable isotopes. For example if we look at atomic number one, we will see two dots. These represent hydrogen (H-1) and deuterium (H-2). For atomic number 8, there are three dots representing O-16, O-17 and O-18.

Looking at the general shape of the dot distribution, we can draw the simple conclusion that for light nuclides the number of neutrons is nearly the same as the number of protons. There are some exceptions, such as H-1, which has only one proton. For intermediate mass nuclides, the neutron to proton ratio is higher, about 1.3. (For Rh-103, n:p = 1.29.) For the heavy nuclides the ratio goes up to about 1.5, e.g., for gold, Au-197, n:p = $\frac{118}{79}$ = 1.5.

In general, we can say that if the neutron-proton ratio is outside of this range the nuclide is unstable. We find for instance that two protons cannot combine to form a nucleus without the aid of neutrons. If we look at the nucleus of He-3, we see that it contains two protons and one neutron. The neutron helps "dilute" the electric force, which tends to push the protons apart. In a sense, the neutron "glues" the protons together. Excess neutrons permit the short-range attractive force between adjacent nucleons to overcome the long-range repulsive electric forces among the protons. In He-4, 2 neutrons and 2 protons give a nucleus with the nucleons very tightly bound together.

Adding more neutrons does not always increase stability. There is no evidence that He-5 exists, and He-6 (which has been observed) has less than a 1 s half-life. In general, extra neutrons aid stability but too few or too many neutrons cause instability. Unfortunately we cannot specify it much closer than that.

For example, look at Cu-64, (Z = 29). You will not find a dot for it on the graph because it is unstable. Yet, if we do plot it we find it sits right between Cu-63 and Cu-65, both of which are stable. Having a n:p ratio in the right range is important for stability but some unstable nuclides also have n:p ratios in the right range. We are safe in saying that everything away from the stability line is unstable; the neutron proton ratio must be "right" for a stable nuclide. Most, but not all nuclides with n:p ratios along the stability line are stable.

We have already seen that all of the very heavy nuclides (Z > 83), are unstable. If they have a suitable n:p ratio (and thus do not beta decay) they will α decay because of the large repulsive electric force. If extra neutrons are present to dilute this electric force, α decay may be prevented but beta decay occurs because of the high n:p ratio.

4.1 Neutron Rich Nuclides

For lighter nuclides a relatively easy way to get a "wrong" n:p ratio is to add a neutron to a stable nuclide (by neutron absorption). For example, adding a neutron to the nucleus of O-18 gives O-19, which is unstable. Conversion of a stable nucleus into and unstable one is called activation. Neutron absorption does not always cause activation. For example, adding a neutron to H-1 produces the stable H-2 nuclide.

Another way to get nuclides that are neutron rich is to split (fission) a heavy nuclide into two intermediate mass nuclides. These fission products are almost certain to be unstable. (Occasionally an uneven split leaves one stable fission product.) Consider splitting a nucleus of U-235. Its n:p ratio is about 1.55. The two fission products are also likely to have n:p ratios near 1.55, too high for nuclides near the middle of the mass range. The dashed line in Figure 4.1 shows the position of all nuclides with a neutron to proton ratio of about 1.5. Only the heaviest stable nuclides lie squarely on this line.

Suppose for example that two fission products are ${}^{95}_{36}Kr$ and ${}^{139}_{56}Ba$.

If we plot these on the graph, we find that they are quite far from the stability zone. They will decay or disintegrate by emitting a particle. Will the particles be alphas or betas? Well we can make a guess.

Perhaps ${}^{95}_{36}Kr$ is an alpha emitter.

$${}^{95}_{36}Kr \rightarrow {}^{91}_{34}X + {}^{4}_{2}\alpha \text{ ?}$$

Where would this new nuclide plot? Is it more stable, less stable or about the same? You should suspect that its stability is about the same and alpha decay is unlikely. So let's second guess (it's usually more reliable) and try a beta decay.

$${}^{95}_{36}Kr \rightarrow {}^{95}_{37}X + {}^{0}_{-1}\beta \text{ ?}$$

How does this one look on the graph? Yes, it looks better. We assume therefore that beta emissions are likely. Experiments confirm this. Because most fission products have too many neutrons, they decay by beta decay. A few unstable fission products release a neutron immediately following beta decay. (These are called delayed neutrons.) No fission products emit alpha particles.

4.2 Interchangeable Nucleons

For beta emissions, notice that the number of nucleons remains constant although the nuclides have changed. Inside the nucleus, a neutron has changed into a proton.

$${}^{95}_{36}Kr \rightarrow {}^{95}_{37}Rb + \beta^{-}$$

$$\left.\begin{array}{r} 36\ protons \\ +59\ neutrons \end{array}\right\} \rightarrow \left\{\begin{array}{l} 37\ protons \\ +58\ neutrons \end{array}\right. + \beta^{-}$$

The reverse process can also happen in some nuclides. A proton can turn into a neutron, either by emitting a positive electron or by capturing an orbiting electron, as described next.

4.3 Neutron Deficient Nuclides

There are many neutron deficient nuclides, (nuclides that plot beneath the curve in Figure 4.1), but we are not likely to meet with them in our reactor technology. What type of emissions should we expect from them? Try some guesses as we did in the last section. Are they alpha emitters? Are they beta emitters? Satisfy yourself that neither of these is reasonable.

These neutron deficient nuclides decay by either positron emission or electron capture or both. Positron? What is that? The positron is a positively charged electron. It is “exactly” like an electron, except for its positive charge. We saw in the last module that an electron and positron can annihilate one another, emitting a pair of gamma rays.

Putting positron emission into the usual symbolic form yeilds:

$$\square{}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}X + {}^{0}_{+1}\beta$$

If you plot ${}^{A}_{Z-1}X$ on Figure 4.1, you will see that it is closer to the stability region than ${}^{A}_{Z}X$.

For electron capture (also called K-capture because the electron comes from the K-shell orbit) we write:

$${}^{A}_{Z}X + {}^{0}_{-1}e \rightarrow {}^{A}_{Z-1}X$$

The nuclide produced is the same one produced by positron emission. In each case, a proton inside the nucleus has turned into a neutron.

4.4 Heavy Nuclides

For nuclides above atomic number 83 we find there are several possible decays. Most of the naturally occurring heavy nuclides emit alpha particles. Some emit beta particles, and a few may also undergo spontaneous fission. Some synthesized heavy nuclides are also positron emitters (rare) or undergo electron capture (more likely).

4.5 Summary of Key Ideas.

- The n:p ration or a nuclei is a predictor of its stability against beta decay

- For light nuclei the n:p ratio is in the neighborhood of 1:1 for O-16, C-12, B-5. The ratio increases to about 1.5 for the heaviest nuclei: U-235, Au-197

- Fission products usually have a n:p ration that is too high for the mass of the fission product

- If nuclei are bombarded with neutrons, they absorb some of the neutrons and will tend to become neutron rich.

- Sometime a delayed neutron will be released following a beta decay.

- Neutron deficient nuclei decay by positron (anti-electron) emission or electron capture.

- Heavy nuclei can decay by numerous means: alpha, beta, spontaneous fission.

4.6 Assignment

1. Why do all nuclides except H-1 have neutrons in their structure?

2. Guess which type of particle the following nuclides emit. Use the graph of Figure 4.1 and then check your answers using a chart of the nuclides or Table of Isotopes (e.g. in the Science Data Book).

3. Sr-90, Br-87, Xe-135, I-135, I-131, Sm-149, Co-60, B-10, N-16, U-238, Pu-239, Cu-64, Mn-56, H-3, Cs-137.

4. What happens if the neutron to proton ratio of a nuclide is too high or too low?

5. For the natural heavy nuclide U-238, write down the stages in its decay to become a stable nuclide. Use a chart of the nuclides. You can repeat the exercise with U-235 as the starting nuclide