NUCLEAR STABILITY AND INSTABILITY

OBJECTIVES

At the conclusion of this course the trainee will be able to:

1. Discuss the stability of nuclides in terms of neutron proton ratios and nuclear forces.
2. From a plot of n against p state the emission a given nuclide is likely to undergo.
3. Given a chart or table of nuclides, list all members of the decay chain of a given radioactive nuclide.

NUCLEAR STABILITY AND INSTABILITY

A plot of all the stable nuclides is shown in Figure 3.1. Each black dot 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 one (H-1) and hydrogen two (H-2). If we look at atomic number 8, we will see 3 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 approximately equal to the number of protons. There are of course some exceptions, such as hydrogen-1 which has only 1 proton. For intermediate mass nuclides the neutron to proton ratio tends to be higher say about 1.3, e.g. 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 nucleons to overcome the long range repulsive electric force between the protons. In He-4 the 2 neutrons and 2 protons give a nucleus which is particularly stable in terms of nuclear behavior.

Adding more neutrons won't always increase the stability. There is no evidence that $^{5}_{2}He$ can exist and $^{6}_{2}He$ (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 will cause instability. Unfortunately we can't specify it much closer than that.

Suppose we 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 however in saying that the neutron proton ratio must be "right" for a stable nuclide. If it is "wrong" the nuclide is certainly unstable.

We've already seen that the very heavy nuclides (Z > 83), are all 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.

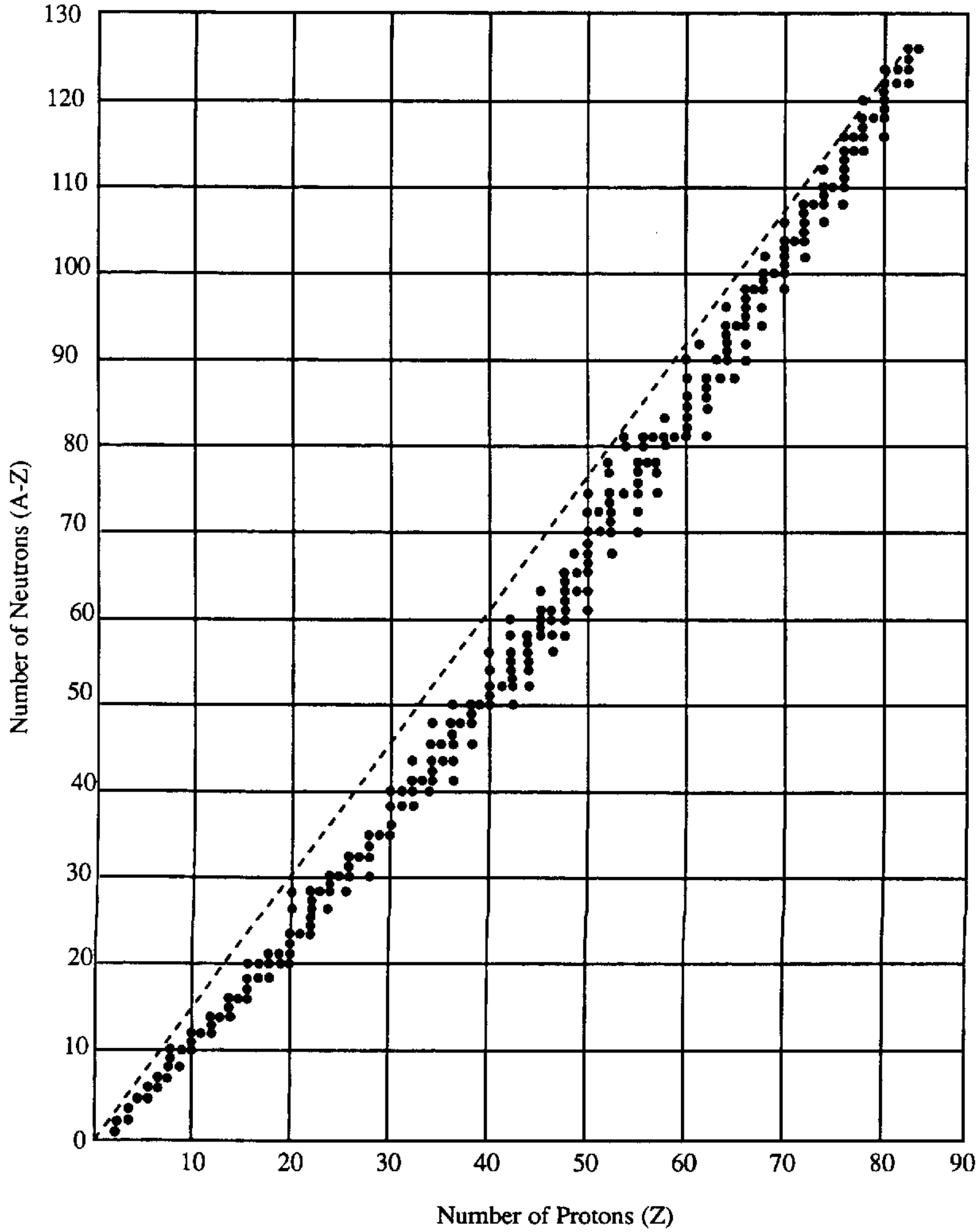
130
120
110
100
90
80
70
60
50
40
30
20
10
0
Number of Neutrons (A-Z)
10
20
30
40
50
60
70
80
90
Number of Protons (Z)

Figure 3.1

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 would give O-19 which is unstable. This process is called activation. Neutron absorption does not always cause activation e.g. add a neutron to H-1 and get the stable H-2 nuclide.

A second way to get nuclides which are neutron rich is to split (fission) a heavy nuclide into two intermediate mass nuclides. These fission products are almost certain to be unstable. Consider splitting a nucleus of U-236. It has an n:p ratio of 1.56 and the two fragments will likely also have n:p ratios around 1.56. This is too high for nuclides around the middle of the mass range. The dashed line in Figure 3.1 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 a way off the stability zone. They are unstable. 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.

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

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.

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

How does this one look on the graph? Yes, it looks better. We can assume therefore that beta emissions are likely. This is confirmed by experiment. The fission products are nearly all neutron rich beta emitters. A few turn out to be stable. A very small number follow a beta decay with the immediate release of a neutron. (These are called delayed neutrons.) There are no fission products at all that emit alpha particles.

Interchangeable Nucleons

In the case of beta emissions you will notice that the number of nucleons remains constant even though the nuclides have changed. What has happened is that a neutron has changed into a proton.

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

$$\left.\begin{matrix} 36 \text{ protons} \\ +59 \text{ neutrons} \end{matrix}\right\} \longrightarrow \beta + \left\{\begin{matrix} 37 \text{ protons} \\ +58 \text{ neutrons} \end{matrix}\right.$$

As you will see in the next section 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.

Neutron Deficient Nuclides

Many neutron deficient nuclides are known, but we are not likely to meet with any in our reactor technology. These nuclides will plot beneath the curve in Figure 3.1. 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? You should be able to satisfy yourself that neither of these seems to be 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 in every way, except for its positive charge. Putting this into the usual symbolic form:

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

If you plot $_{Z-1}^{A}X$ on the graph, Figure 3.1, you will see that it is closer to the stability region then $^{A}_{Z}X$.

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

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

The nuclide produced is the same one produced by positron emission.

Heavy Nuclides

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

ASSIGNMENT

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

2. For these nuclides guess which type of particle they will emit. Use the graph of Figure 3.1 and then check your answers from a chart of the nuclides or from the Table of Isotopes in the Science Data Book.

   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.

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

4. 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 or the Science Data book for this. The exercise can be repeated for U-235 as the starting nuclide.

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