Modes of radioactive decay

There are 4 very standard modes of radioactive decay:

$$\alpha : \Delta Z = -2, \Delta A = -4$$

$$\beta : \Delta Z = +1, \Delta A = 0$$

$$\gamma : \Delta Z = 0, \Delta A = 0$$

$$\beta^{+}(ec) : \Delta Z = -1, \Delta A = 0$$

Thus you can go either up or down the periodic chart by each of these decays. How you determine is the nucleus is stable against a particular decay mode is by calculating the energies of the constituents.

However, the ultimate method is by observing a particular decay mode. I've provided a decay scheme that we can work through to find the decay modes. We do have some general criteria for stability:

(1) all isotopes with proton number greater than 83 (Z>83) are unstable

(2) (a) most even-even nuclei are stable

(b) many odd-even or even-odd nuclei are stable

(c) Only 4 odd-odd nuclei are stable (2H, 6Li, 10B, 14N)

(3) Stable nuclei with mass numbers less than 40 (A<40) have approximately the same number of protons and neutrons.

Stable nuclei with mass numbers greater than 40 have more neutrons than protons.

Example: Is $^{38}_{16}\mathrm{S}$ likely to be stable?

(1) It has Z<83 so (1) is satisfied.

(2) This is an even-even nucleus so (2) is satisfied.

(3) This is not satisfied since there are more neutrons than protons. In fact, A=38, Z=16 so N=22 here.

This particular nucleus is unstable to beta decay.

We can calculate this:

for beta decay, we have z->z+1 and N->N-1. We would thus consider the nucleus:

$^{38}_{17}\mathrm{Cl}$:m=37.96800995u

$^{38}_{16}\mathrm{S}$:m=37.97116470

β:m=**electron mass = 0.000548580152 atomic mass units**

Here is a link that is quite useful for these types of calculations:

http://www.tunl.duke.edu/nucldata/links.shtml

and in particular, you will find this useful:

http://t2.lanl.gov/data/map.html

The binding energy of a nucleus $^{A}_{Z}\mathrm{X}$ against dissociation into any other possible combination of nucleons, for example nuclei R and S is:

We can calculate the binding energy:

$$B = \left[M(R) + M(S) - M\left(^{A}_{Z}X\right) \right] c^2$$

Thus:

$$B = [37.96800995 + 0.000548580152 - 37.97116470] \times 1.49241713 \times 10^{-10} \mathrm{J/amu}$$

$$B = -2.606 \times 1.49241713 \times 10^{-10} \mathrm{J} = -3.889 \times 10^{-13} \mathrm{J}$$

The statement above is in agreement with the negative result for the binding energy. This example calculation now provides you with great insight into how to determine, for example, the release of energy in an atomic reaction. In particular let's turn our attention to Uranium.

Uranium is unique because it is fissionable which means that it can be separated into daughter nuclei which is accompanied by the release of rather tremendous amounts of energy, and perhaps neutrons. These neutrons go on to stimulate fission to occur in other nuclei. This process is quite unique and distinct from a normal decay process since this decay can be stimulated by means of neutron interaction. Although you might think that fast neutrons are better, in fact it is the slow or thermal neutrons which are most effective at producing nuclear fission to occur.

Here is a very good reference to information about uranium and its background:
http://www.ccnr.org/decay_U238.html
Here is a particular address that I found interesting:
http://www.ccnr.org/salzburg.html

One very interesting process which you will no doubt also be interested in is just how plutonium is produced.

Now let's look at a particular fission reaction:

$$^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \rightarrow \left(^{236}_{92}\mathrm{U}^{*}\right) \rightarrow ^{140}_{54}\mathrm{Xe} + ^{94}_{38}\mathrm{Sr} + 2\left(^{1}_{0}\mathrm{n}\right)$$

We want to calculate the amount of energy released by this reaction.

I would also like to note that other products are possible from this fission, some of which may produce as many as 5 neutrons, such as:

$$^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \rightarrow \left(^{236}_{92}\mathrm{U}^{*}\right) \rightarrow ^{150}_{60}\mathrm{Nd} + ^{81}_{32}\mathrm{Ge} + 5\left(^{1}_{0}\mathrm{n}\right)$$

I also want to note that only a few nuclei undergo fission like this, for example $^{235}_{92}\mathrm{U}$ and $^{239}\mathrm{Pu}$ have large cross sections for slow neutrons while $^{232}\mathrm{Th}$ has a greater cross section for fast neutrons.

Now instead of actually using the calculation previously used, we can obtain an approximate result for the energy released by fission by looking at the binding energy per nucleon curve. When a nucleus such as uranium splits, the result is to increase the binding energy per nucleon from about 7.8 MeV to about 8.8 MeV which releases about 1 MeV per nucleon. With about 234 nucleons involved in the process we get about 234 MeV of energy released which is about

$$234\text{x}1.60217646 \times 10^{-13} \text{ Joules} \approx 1\text{x}10^{-11}\text{J}$$

The whole key to the process is to have enough atoms involved (billions and billions) so that the energy release becomes quite significant.

However, just getting the material together is not the whole deal. You need to get it together in such a way that the surface area to volume ratio is maximized, which essentially means a spherical shape. It also needs to be done quickly and held together which means explosive shape charges.

All of this has to happen inside of a container of significant strength which probably means titanium.

Now most of the uranium is made of ^{238}U which is not fissionable. Only about .7% of ^{235}U exists and this needs to be separated. This separation is quite difficult since it needs to rely upon a technique that can distinguish between the mass of about 3 neutrons. This ultimately means high speed centrifuges are required. This is the so-called Uranium enrichment process. There are, however, other techniques to do this. You will from time to time hear the term “yellowcake” used in reference to the enriched uranium.

Uranium 238 can also be used to produce a form of plutonium which is also fissionable, however this plutonium is extremely toxic.

Now one question you may also have is how do you slow neutrons down in order for the fission process to occur? There are several methods, one is to use ordinary water and the other is to use graphite. Both of these materials tend to slow neutrons and ultimately prevent run away reactions from happening. You may see control rods being inserted into reactors ... the rods are being placed there to almost completely absorb neutrons. Partial insertion of the rods results in a slowing of the process (or perhaps a hastening due to increased cross sections). To produce plutonium from the uranium, often the reactors are surrounded by deuterium (D2O) rather than H_2O since the D_2O does not absorb neutrons as readily as water does. These are the “heavy water reactors” which are often used in Canada.

There is yet one more type of nuclear reaction which we won’t go into in great depth. This is the process of nuclear fusion. An example of such a reaction is this:

$$^{1}_{1}H + ^{1}_{1}H \rightarrow ^{2}_{1}H + ^{0}_{+1}e + \gamma$$

$$^{1}_{1}H + ^{2}_{1}H \rightarrow ^{3}_{2}He + \gamma$$

$$^{2}_{3}He + ^{2}_{3}He \rightarrow ^{4}_{2}He + ^{1}_{1}H + ^{1}_{1}H$$

This series of reactions is called the “proton-proton” cycle and it is probably one of the primary processes that allows the sun to operate.

Another example of a fusion reaction releases energy and neutrons:

$$^{2}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{0}n$$

For this reaction you can calculate the energy released pretty easily:

$$E = [2.014102 + 3.016049 - 4.002603 - 1.008665] \text{x} 1.49241713 \times 10^{-10} \text{J/amu}$$

here you get a result of about 17.6 MeV or about $2.8 \text{x} 10^{-12}$ J

Reactions such as these are hopefully going to be our energy producers of the future, however, that future is still probably about 30-50 years away.