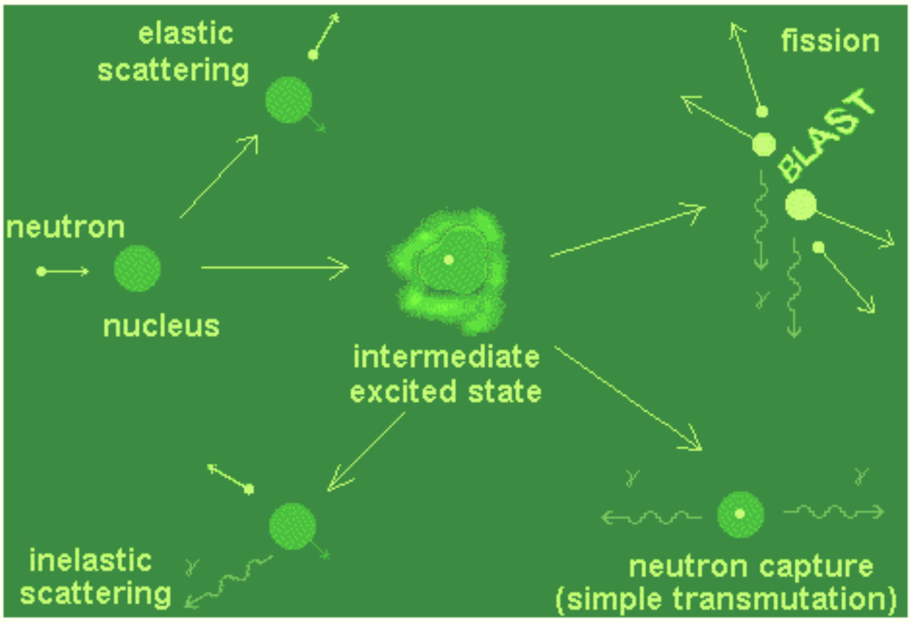
What happens in the reactor

Probably fission, right?

Actually, probably not. Those who think that the idea is that U-235 is merely turned into fission products and energy until there's almost nothing left should really read this section. I did my best to keep it as easy as possible, without turning it into non-information (that's when they want you to accept facts or half-truths without being able to really think about them).

Since reactor technology is not our focus, we will concentrate merely on the micro scale phenomenons. We are not particularly interested in the question *why* certain nuclei may fission, we will only try to understand *when* and *to what extend* this happens. There are two possible interactions between neutrons and nuclei, shown in figure 1 below.

Figure 1: Most likely interactions between nuclei and neutrons



The first mechanism is **scattering**, which changes the velocity (energy) and direction of the neutron (like when you trow a marble onto a football). This can be both elastic or inelastic. In the latter case the neutron transfers a large part of its energy to the nucleus that changes its energy state, usually followed by "relaxation", emitting some excess energy as gamma radiation.

The second type of interaction is **absorption**, in which the neutron is being "used up". It can either become **captured in the nucleus** resulting in a new isotope, or it can lead to **fission** resulting in two smaller nuclei and a few very high velocity neutrons. The kinetic energy of the fission products (and neutrons) is determined by a small decrease in total mass compared to the original nucleus, as follows from Einstein's $E=mc^2$. By collisions this energy is transferred to the cooling water and by use of a heat exchanger (in PWRs) and a steam generator one can produce electricity.

One example of the many possible fission reactions for uranium-235 is:

uranium-235 + 1 neutron ==> barium-144 + krypton-90 + 2 neutrons

The energy release per fission is about 200 MeV. On average, each uranium fission event releases 2.46 neutrons. But uranium-235 can also capture that neutron by:

uranium-235 + 1 neutron ==> uranium-236

which is non-fissile. All absorption processes other than fission are called transmutations. Capture is the simplest and most predominant transmutation mechanism.

So now we know that a nucleus in order to be fissile should have a high absorption probability relative to the scattering probability. But suppose that there is indeed a very high absorption chance, but the result of absorption would much more often be capture instead of fission. This isotope would still not be suitable. These things can -- of course -- be measured, and to a certain extend even calculated from theory. Combining the best of both, much work in this field is now being done using computer simulation.

So, how can you tell?

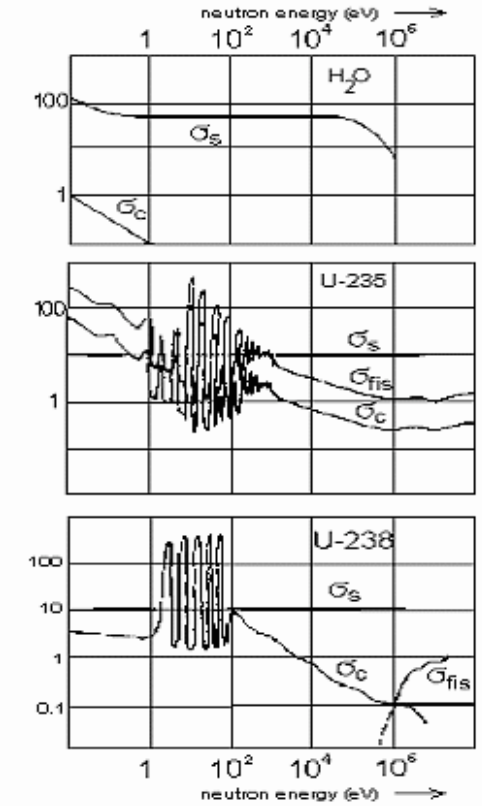
In figure 2 below you can see the cross sections (in barns) for **s**cattering, **c**apture and **fis**sion depending on the neutron energy for water, for fissile uranium-235 and for non-fissile uranium-238. Cross sections are some measure of probability, only the *amount* of material is not included. Please take some time to compare the plots. They contain almost everything we need to basically understand reactors. And if we include radioactive decay, especially when half-lives are short compared to the time spent in the reactor, we can understand and predict reactor inventories.

Fast neutrons released upon fission have an energy of 1 to 2 MeV. LWRs, like all designs that include neutron moderation, are thermal reactors, which means that they are designed to create fission with slow neutrons, that's below 1 eV. You can see why in the plot in the middle: That's when the probability for fission of a uranium-235 nucleus becomes very high, meaning that if by collision such a slow neutron is absorbed into the nucleus it has a good chance to fission.

However, it may also capture the neutron and become a non-fissile uranium-236 nucleus. Since sustaining a chain reaction requires one slow neutron inducing fission to result in exactly one new slow neutron for another fission event, the number of neutrons available for fission is determined by the neutron leak (other nuclei in the fuel that capture neutrons, the fuel containment material, surrounding material...) and by the necessary control measures.

Bouncing against hydrogen atoms in the cooling water, the neutrons lose nearly all their velocity (energy). In the first plot you can see that the scattering cross section for neutrons is high almost throughout the whole spectrum. That is because a hydrogen nucleus (a proton) an a neutron are of the same size. Big nuclei are much more "transparent" for neutrons.

Figure 2: Cross sections (barns) for scattering, capture and fission in water, U-235 and U-238



The curve ultimately declines as the neutron energy becomes so high that it can pass a hydrogen atom on relatively short distance without interacting (without "feeling" its presence). You can also see why water is not the perfect moderator: In the low energy range it is also able to capture neutrons. Please don't confuse the moderation function and the cooling function of the water. Since almost all kinetic energy released upon fission is carried by the fission products, the cooling is merely a result of molecule to molecule collisions. The water plot contains no information about this.

The plot in the middle shows the general behaviour of nuclei which we call fissile: The cross section for fission is higher than for capture (although they do compete) and both are above the scattering curve. The fissile plutonium isotopes (239 and 241) in general show the same behaviour. Since capture always plays a major role in the thermal range it should be clear that **in a thermal reactor neither uranium nor plutonium can ever be totally "burnt up".** Also, since criticality need to be maintained in order to "work" a reactor (this implies a certain minimum amount of fissile material at each moment), **neither the fissile uranium nor the fissile plutonium can be completely converted by both fissions and transmutations.**

The bulk material of uranium-238, and in general any non-fissile nucleus, behaves very differently. You can see that only for fast neutrons fission is actually possible, and even then capture totally dominates. In LWRs, a fraction of about 1% of the U-238 is observed to fission directly by fast neutrons (which amounts to some 5% of all fissions). This can be derived from the plot, since the cross section for scattering -- upon any heavy nucleus really -- is about 100 times as big. You should note that scattering (slowing down) in this case always pushes towards capture. This is how an unstable U-239 nucleus is formed, which decays rapidly first to neptunium (Np-239) and subsequently to plutonium (Pu-239). There are some more routes starting from U-238 or even U-235 that ultimately lead to the formation of Pu-239, but they're less likely.

Because Pu-239 is fissile, U-238 is sometimes called a **fertile** or a **breeding** material. Same thing with Pu-240, which is formed through Pu-239 capturing a neutron, and Th-232 which is much more abundant than natural uranium and which was to be the pot of gold in the eyes of the nuclear society. The thorium cycle is still seen as the ultimate goal, using breeder reactors to produce the fissile U-233, which essentially is much like U-235 or Pu-239. This is a very important reason for them to hold on to reprocessing, since this is crucial for the full development of nuclear energy's potential through U-233 breeding.

Transuranics

Plutonium, especially the Pu-239 isotope, is of vital importance to keep an LWR going. Ultimately, more than one third of all fission events are plutonium fissions. As burnup rates keep on increasing, this can even go up to about half of all fissions. A higher U-235 enrichment leads to a higher burnup by means of more plutonium fission, not uranium. Since part of the U-235 will be transmuted to non-fissile U-236, which only "eats" neutrons, it is actually the plutonium maintaining the reactivity of the reactor core. While the neutron leak increases, the plutonium provides an extra neutron source. The non-fissile (even numbered) plutonium isotopes behave like U-238, the fissile (uneven numbered) ones behave like U-235. There is an important difference though: Both Pu-239 and Pu-241 have somewhat higher fission and capture cross sections than U-235, which in itself is not bad news, but they also fall more closely together. This means that **the fissile plutonium isotopes are not such good fuels for thermal reactors as U-235.**

Neptunium is the first transuranic element, plutonium the next, and there are more. The Pu-241 isotope decays rather quickly through beta emission. The product is americium-241 (Am-241). With a half-life of about 14 years and typical irradiation periods of 3 or 4 years, only some 10% of the Pu-241 will be changed into Am-241. However, if the fuel is reprocessed and the plutonium remains in stock for several years before re-use, Am-241 becomes a problem and it might be necessary to remove it. In a reactor Am-241 is easily transmuted to Am-242, which is very unstable (half-life 16 hours). Through beta decay this gives rise to yet another transuranic, curium. Most of the curium, however, is a decay product of Am-243, which in turn is a decay product of Pu-243. Pu-243 is highly unstable with a 9 hour half-life. This is why the plutonium "chain" of successive neutron capture ends with Pu-242.

I really hope you've noticed by now that beta decay plays a major role in all this. If through capture a nucleus is formed that is only stable for several days, you can forget about a next transmutation -- imagine how small the chances are for that particular nucleus to meet another neutron. Also, by keeping track of the number of transmutations necessary to create a certain isotope you can get a rough indication about the relative amount of that isotope one can expect to find in spent fuel. It's the transuranics that make up the long term waste problem. They are all unstable, some decay very fast through beta emission which determines their behaviour in the reactor, others show slower alpha decay. Fast alpha-emitters (that is like a half-life of several decades) tend to cause problems when reprocessing, the slower ones remain radiotoxic for thousands of years. And finally, some are fissile. In general this is the case when neutron and proton numbers are of different parity (if you don't understand this, never mind).

If you came this far you might as well have a look at the table below, showing the most predominant reactions. Remember that on reactor start-up, we only have a lot of U-238 and a bit of U-235. One might also make some kind of plot of this, but in my opinion that merely serves those who are familiar with the periodic system and I don't expect most readers to be so. With this, you can tell how one isotope gives rise to another. The half-lives tell you what transuranics still will be a problem in the 22nd century, and way beyond. And yes, it is possible to create even heavier isotopes, some of which are so unstable that they show total spontaneous fission within. What a way to decay. Of course, transmutation was also the way to discover new elements. Theory predicts that after a series of extremely unstable elements, there will be heavier ones with longer lifetimes.

Table of most important isotopes in a reactor, parents and decay:

92. uranium	Mother (mechanism)	Behaviour	Decay, half-life
U-234	U-235 (n,2n)	RepU fuel contaminant	a 2.4E+5 y
U-235	natural resources	fissile	a 7.0E+8 y
U-236	U-235 (n capture)	neutron poison	a 2.3E+7 y

U-237	U-236 (n capture)	unstable	b 6.8 d
	U-238 (n,2n)		
U-238	natural resources	fertile (Pu-239)	a 4.5E+9 y
U-239	U-238 (n capture)	unstable	b 23 min
93. neptunium	**Mother (mechanism)**	**Behaviour**	**Decay, half-life**
Np-237	U-237 (beta decay)	neutron poison	a 2.1E+6 y
Np-238	Np-237 (n capture)	unstable	b 2.1 d
Np-239	U-239 (beta decay)	unstable	b 2.4 d
	Np-238 (n capture)		
94. plutonium	**Mother (mechanism)**	**Behaviour**	**Decay, half-life**
Pu-238	Np-238 (beta decay)	Pu fuel contaminant	a 88 y
	Pu-239 (n,2n)		
	Cm-242 (alpha decay)		
Pu-239	Np-239 (beta decay)	fissile	a 2.4E+4 y
Pu-240	Pu-239 (n capture)	fertile (Pu-241)	a 6.5E+3 y
Pu-241	Pu-240 (n capture)	fissile, fast decay	b 14 y
Pu-242	Pu-241 (n capture)	neutron poison	a 3.8E+5 y
Pu-243	Pu-242 (n capture)	unstable	b 8.8 h
95. americium	**Mother (mechanism)**	**Behaviour**	**Decay, half-life**
Am-241	Pu-241 (beta decay)	Pu fuel contaminant	a 432 y
Am-242	Am-241 (n capture)	unstable	b 16 h
Am-242m	Am-241 (n capture)	meta-stable, fissile	a 152 y

Am-243	Pu-243 (beta decay)	neutron poison	a 7.4E+3 y
	Am-242m (n capture)		
Am-244	Am-243 (n capture)	unstable	b 10 h
96. curium	**Mother (mechanism)**	**Behaviour**	**Decay, half-life**
Cm-242	Am-242 (beta decay)	unstable, fertile	a 163 d
Cm-243	Cm-242 (n capture)	fissile, fast decay	a 29 y
Cm-244	Am-244 (beta decay)	fast decay	a 18 y
	Cm-243 (n capture)		
Cm-245	Cm-244 (n capture)	fissile + neutron poison	a 8.5E+3 y

Notes: (1) Obviously "a" means alpha decay and "b" means beta.
(2) If more than one mother are relevant the most likely is ranked first.
(3) The (n,2n) reactions can always be "reversed" by capture. Capture normally dominates over (n,2n) except in the cases shown here.
(4) Heavier than neptunium: decay through spontaneous fission is possible.
(5) Heavier than Cm-245: capture chances are low.

Both figures 1 and 2 are taken from an excellent article written by Hans-Jurgen Zech ("Reactorphysik"), which was published in "Das ende des Atomzeitalters?" in 1987 as part of a national debate on nuclear energy in former Western Germany. The first is a reproduction, the second a somewhat modified scan.