NUCLEAR POWER

Of all members of the whole “menagerie of powers”, i.e., of various methods of harnessing energy resources, nuclear power is surely the most controversial one, and it evokes the strongest emotions.

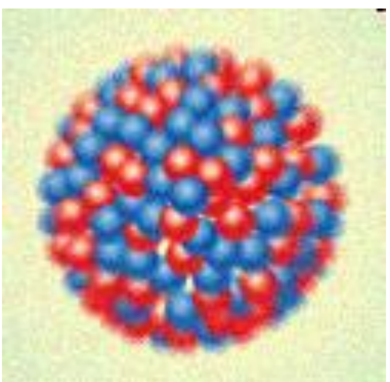
A personal note from the instructor (Dr. Tom): When I was an active researcher in the area of experimental physics – yes, I was, for more than 40 years of my professional life – the topic of my research was to investigate different phenomena in solid state physics by means of neutron scattering. And the principal sources of neutron radiation that can be used for such studies are **nuclear reactors**. So, over the period of 40 years I often spent hours and hours in close proximity of a nuclear reactor (actually, of eight reactors in five different countries). And nothing harmful ever happened to me. So, I am “positively biased”: when I think about nuclear reactors, I don’t think of them as of bloodthirsty wild animals, but rather as of “domestic animals”. Therefore, I know that when I lecture about nuclear power, I have to be extremely cautious. I told you at the beginning that the “battle cry” in this course if ANP, it is, **“Absolutely no propaganda!”**. I will do my best, then, to avoid sneaking in any propaganda when talking about nuclear power – I will present facts only, facts that can be easily verified in widely available sources. OK., this is the end of the personal note!

We have to start with a brief review of fundamental facts in nuclear physics. So, atoms consist of “shells” of electrons, which surround a nucleus – a tiny collection of particles known as “nucleons”: there are two kinds of them, namely, protons (positively charged particles, with a charge of the same magnitude as the negative electron charge) and neutrons (particles only slightly more massive then protons, but with no electron charge). The size of the nucleus is about one hundred thousand times smaller than the size of the atom itself.

Nuclear energy: a member of the "Oldboy's Club" that may be admitted to the "Energy Alternatives Club" because it's green.

We will begin with a short review of radioactivity.

- An atom consists of a positive nucleus, and a "shell" of negative electrons;



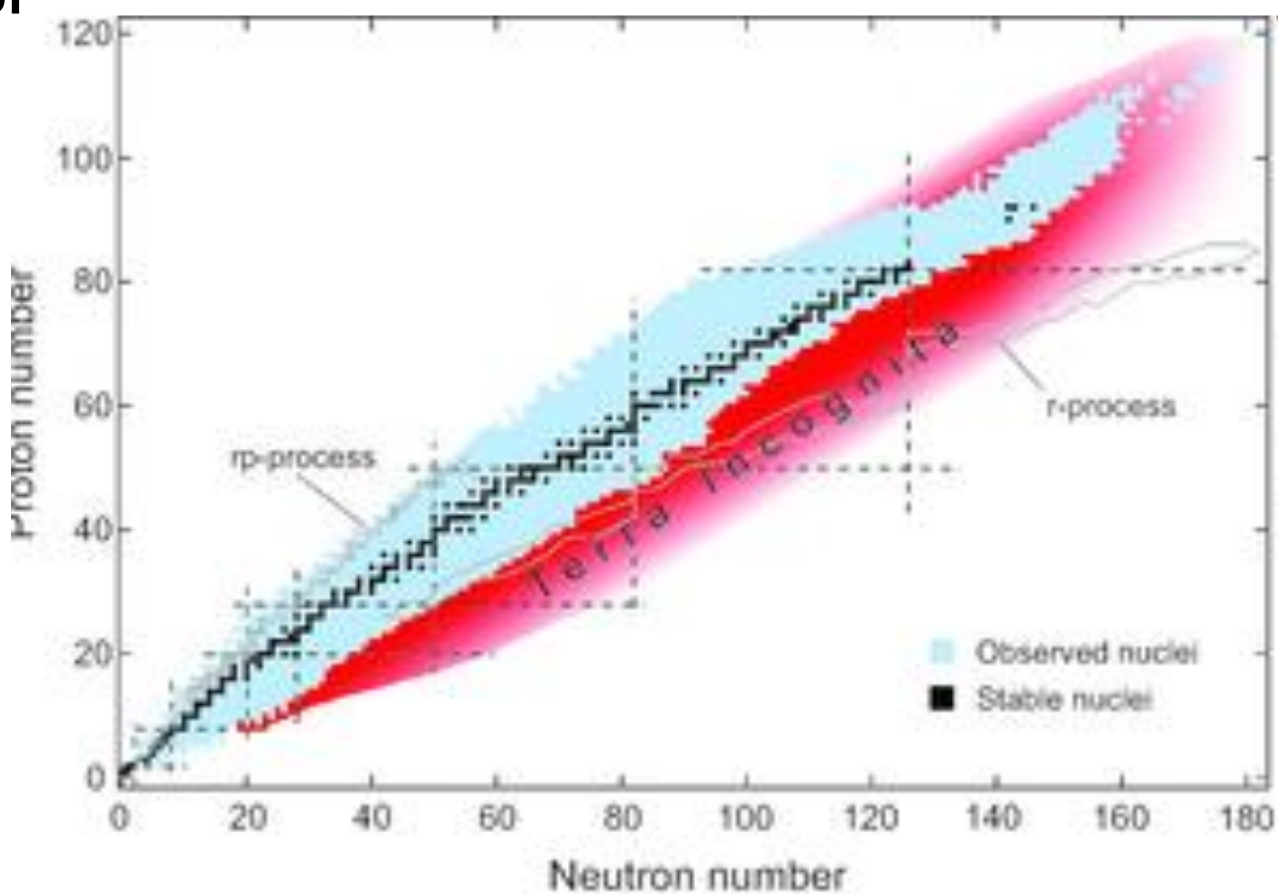
- A nucleus consists of positive protons and neutrons that have no charge. The proton and electron charges are of the same magnitude, but of opposite signs;

- The number of protons in the nucleus is the same as the number of electrons in the electronic shell, so that the atom has a zero net charge.

Particles with positive electric charge repel one another, and protons in the nucleus are so closely packed that these repulsive forces are very strong. So, in atomic nuclei there is an extra *attractive* force that holds all the constituent protons and neutrons together. It's known as the "strong force". It would be too long a story to talk about this force in our course – but if you are interested, much material about strong nuclear forces can be found in the Web, e.g, in this Wikipedia article. The only important fact that we need to point out here is that neutrons play an important role in holding the nucleus together. With the exception of the hydrogen nucleus, consisting of a single proton, there are no other nuclei with no neutrons. And the number of neutrons cannot be too low or too high. The rules are not simple, it's better to use a graph to explain what is going on:

There are stable nuclei, and radioactive (unstable) nuclei, that decay after some time. The “lifetimes” of known unstable nuclei span from microseconds to billions of years.

The figure shows the so-called “Chart of known nuclei”. The stable nuclei – we know about 500 of them – form the so-called “stability path” (black squares in the graph). As you can see, the ratio of the number of protons (Z) to the number of neutrons (N) Is about 1 for the light stable nuclei, and about ¾ for the heavy ones.



There are over 5000 known radioactive (unstable) nuclei.

The graph shows the properties of nuclei depending on the number of constituent neutrons (on the abscissa) and protons (on the ordinate). Black dots indicate stable nuclei, blue dots – unstable nuclei, i.e. such that have a limited lifetime only and eventually undergo a radioactive decay.

By convention, Z is te number of protons in a nucleus, N is the number of neutrons, and A is the total number of all nucleons – therefore, A = Z + N. Also, the convention is that for describing nuclei we use the chemical symbol and put Z as the left subscript and A as the left superscript: ${}^{A}_{Z}$X. One small comment –

Z, the number of protons in the nucleus is equal to the number of electrons in a given atom, because atoms are electrically neutral. So, in fact, writing Z in the nucleus' symbol is redundant. Therefore, Z is often omitted – for instance, instead of ${}^{12}_{6}$C), we more often write simply ^{12}C.

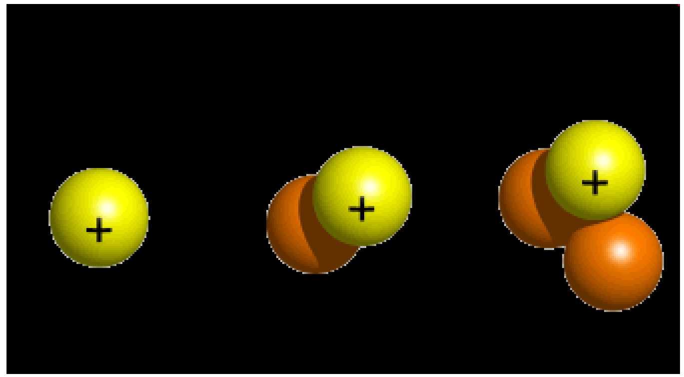
A small comment – sometimes people instead of using the left sub- and super-scripts (it's the official way, sanctioned by international organizations) put Z and A as **right** sub- and superscripts, e.g., as in the picture showing the two carbon isotopes, described in the figure's field as C_6^{12} and C_6^{14} (the figure was copied from somewhere, it's not the fault of the author of the present text). Such "unorthodox" notation seldom leads to misunderstandings, though. By the way, there is an often-used alternative way of describing nuclei – one uses not the chemical symbol, but the full name of the element, starting with a capital, and then a dash and the A number: e.g., Carbon-12, Carbon-14, or Uranium-235.

Note that the number of neutrons in stable nuclei is equal to the number of protons (N = Z, as in some light nuclei, such as, e.g., in carbon $^{12}_{6}$C) or greater, N$>$Z. There is only one known exception from this rule, a stable nucleus with two protons and only one neutron: Z =2 identifies it as helium, so that the full symbol is $^{3}_{2}$He (it's an extremely rare isotope of helium, in ordinary helium nucleus there are two neutrons). For heavier nuclei, the number of neutrons grows faster, than the number of protons. For the heaviest of all stable nuclei, an isotope of lead with A = 208 ($^{208}_{82}$Pb), so that he N/Z ratio is (208-82)/82 = 126/82 = 1.54.

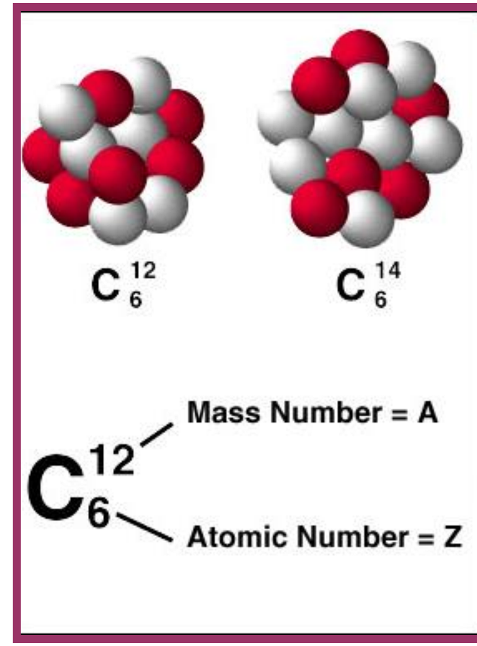
Atoms with nuclei in which the number of protons (Z) is the same, but with different numbers of neutrons, are called *isotopes* of the same chemical element.

The chemical properties of atoms depend on the <u>number of electrons in their shells</u> – or, equivalently, on the <u>number of protons</u> *Z* in their nuclei. Atoms with different number of electrons are different chemical elements:

Z=1: Hydrogen;
Z=2: Helium;
Z=3: Lithium;
Z=4: Beryllium;
…………………
Z=6: Carbon;
…………………
…………………
Z=92: Uranium



Three isotopes of Hydrogen (above); and two isotopes of Carbon (right). Only two are shown, but there are more Carbon isotopes.



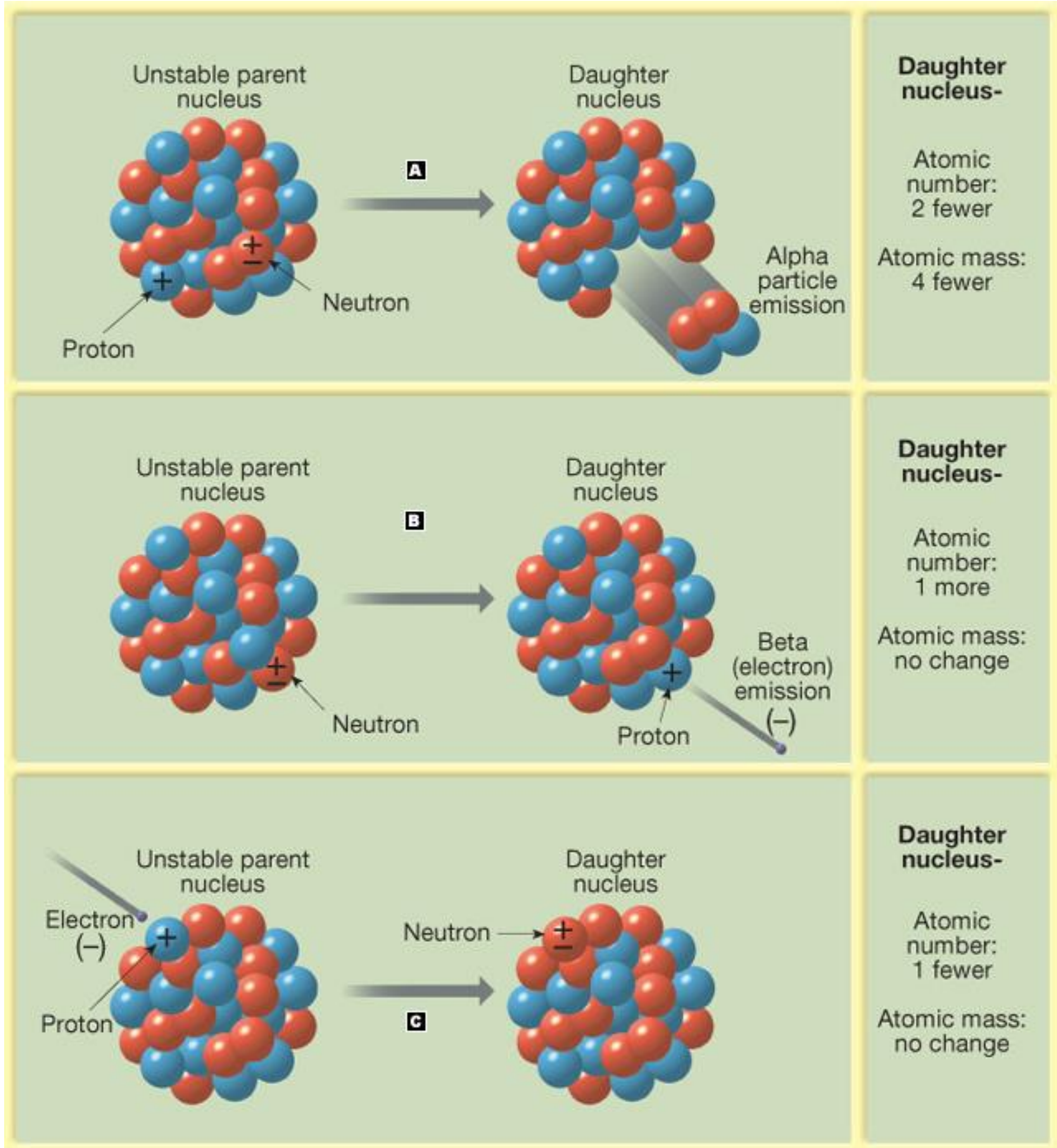
However, there may be several nuclei with the same number of protons *Z*, but a different number of neutrons N. Atoms with such nuclei are all atoms of the same chemical element, but they are different *isotopes* of that element. Some even have special names: *Z*=1, *N*=0 – "ordinary" Hydrogen; *Z*=1, *N*=1 – Deuterium (stable); *Z*=1, *N*=3 – Tritium (radioactive).

Types of radioactive decay:

Alpha-decay (most often, heavy nuclei).

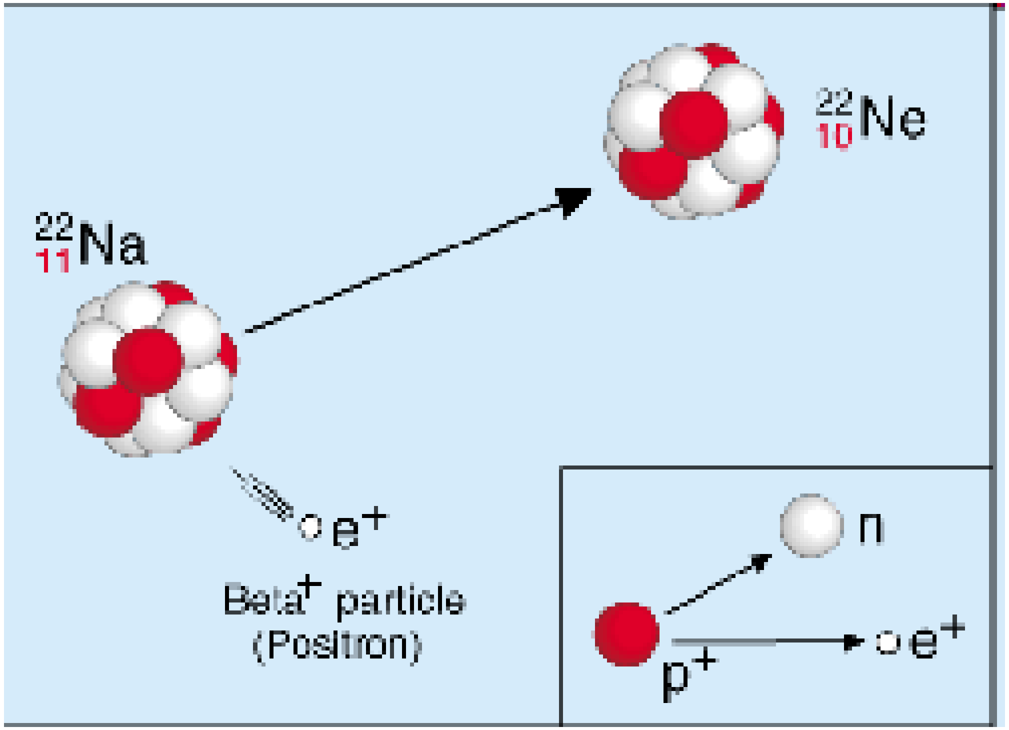
Beta-decay: one Neutron decays, emitting one elec-tron and changes Into a proton. The *Z* number *increa-ses* by 1.

Electron capture: One proton captu-Res one shell ele-Ctron, changing Into a neutron. The *Z* number <u>decreases</u> by 1.

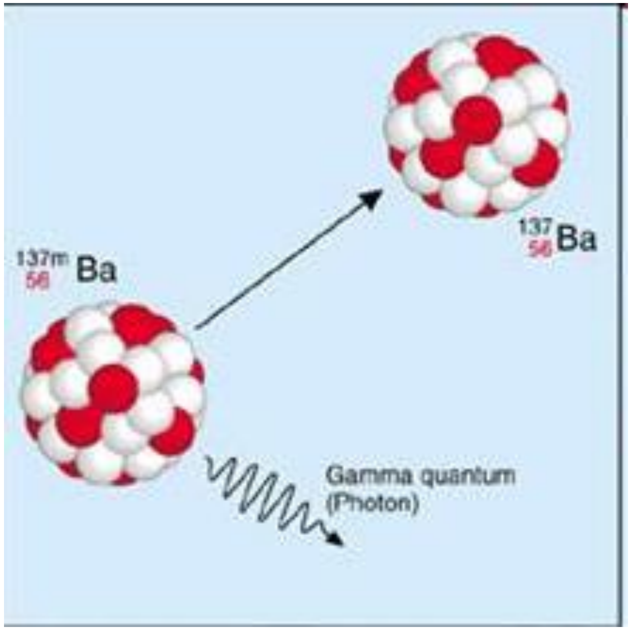


Three more decay types:

Beta-plus decay (or positron emission). One proton emits an "anti-electron", changing Into a neutron. *Z* drops by 1.



Gamma-decay: the nucleus emits a high-energy photon ("gamma quantum"). Never occurs "by itself", it always follows an alpha or beta decay.



Spontaneous neutron emission (no picture). A rare decay type. A small minority of Uranium and Plutonium decay by ejecting a neutron (whereas an overwhelming majority undergo an alpha-decay).

Only one element – Californium, artificially produced in nuclear reactors, is a strong neutron emitter.

Unstable, or radioactive nuclei may decay in several different ways. One is the so-called “alpha-decay”, in which the nucleus ejects an α-particle, which is nothing else than the nucleus of Helium-4:

$$ {}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X} \quad \rightarrow \quad {}^{4}_{2}\mathrm{He} + {}^{\mathrm{A}-4}_{\mathrm{Z}-2}\,\mathrm{Y} + \mathrm{Extra\ energy} $$

So, due to the decay the nucleus “steps down” by two positions in the periodic table, and loses a total of 4 nucleon.

About the β-decay, one can think of as a process in which one of the nucleus’ neutron “spits out” an electron and thus changes to a proton. Therefore, Z **increases** by 1, whereas the total number of nuclei remains unchanged:

$$ {}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X} \quad \rightarrow \quad \beta^{-} + {}^{\mathrm{A}}_{\mathrm{Z}+1}\,\mathrm{Y} + \mathrm{Extra\ energy} $$

Interestingly, there are two more types of β-decay: one, called

“β-plus decay”, in which the nucleus ”spits out” not an electron, but a *positron*, β^+, – the electron’s “twin sister”, a particle with identical mass and a charge of the same magnitude, put of a**positive sign**. One can think of it as of an event in which one of the protons in the nucleus ”spat out” a very light particle which run away with the proton’s charge, changing it to a neutron. Again, the A number remains unchanged, but now the Z number *decreases* by one:

$$^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X} \quad \rightarrow \quad \beta^+ + ^{\mathrm{A}}_{\mathrm{Z-1}}\mathrm{Y} + \mathrm{Extra\ energy}$$

It’s good to know that isotopes experiencing the β^+ decay are used in a novel medical diagnosing technique known as “Positron Emission Tomography” (PET) and therefore are indeed very important.

And the third one og the “beta-decay-triad” is the “electron capture” process. Here one of the nucleus’ protons acts like a chameleon capturing a fly: the animal shoots out its long and sticky tongue, the fly gets “glued” to it, and the chameleon swallows it. Neutrons have no tongues (at least we think so), but otherwise the process is similar, the proton captures and swallows one electron, which neutralizes its positive charge and the proton is transfigured to a neutron. Hence, the overall reaction can be written as:

$$ {}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X} + \beta^{-} \quad \rightarrow \quad {}^{\mathrm{A}}_{\mathrm{Z}-1}\mathrm{Y} + \text{Very little extra energy release} $$

In books and Web documents one can often read about a third kind of redioactive decay – the “γ-decay. In the “heroic epoch” of research on radioactivity, it was discovered that radioactive materials emit ”radiation” of three different kinds, the aforementioned α-radiation and β-radiation, and a third kind that was given the name of “γ-radiation”. The pioneers in radioactivity research then believed that there are three different types of decay, each producing a different radiation. However, **it is not so** – there is no such thing as a “gamma decay standing by itself”. The acts producing the gamma rays (which are photons, members of the same family as visual light photons, but of much higher energy) is always a **sequel** to an earlier α or β decay, and it’s a process which the decaying nuclei use for “getting rid” of what in the reaction equations above was called the “Extra energy”.

The “HALF   LIFE” of radioactive elements

Radioactive decay is a “stochastic” process, i.e., not a “deterministic” process, but a process ruled by the laws of statistics. If you take a single atom of a radioactive isotope, you cannot predict how much time will elapse before the decay process happen. Only for a large number – call it *N* – of atoms of an isotope, one can predict how much time will pass to the moment the population decreases to *N/*2. His time is called the “half life” of a given isotope. The values differ significantly from one isotope to another, for some it’s microseconds, and for some – billions of years. This is the “minimum” I want you to know – if you wish to learn more, here is a good Web source on the topic – and you may find many more using Google.

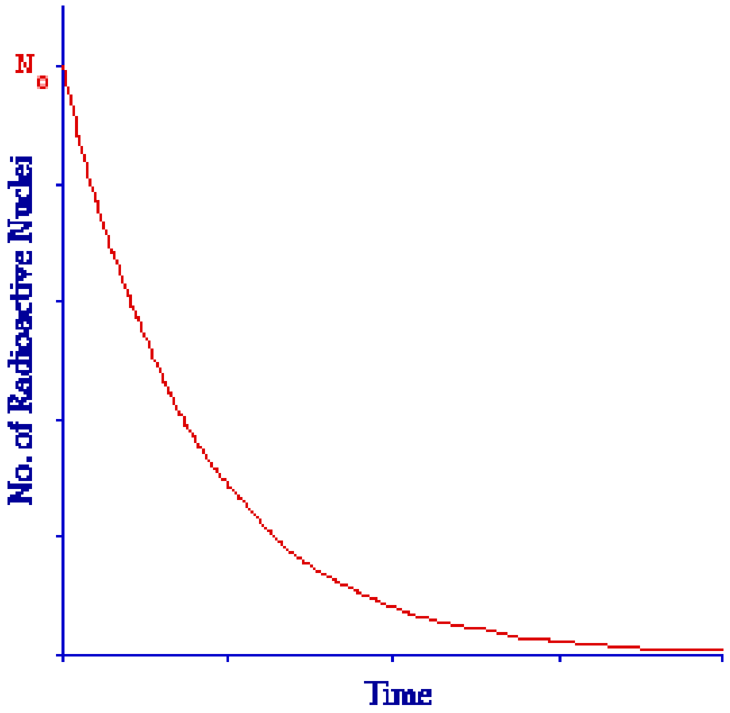
The next two pages of graphs – we will skip them this year (but, of course, you may read them, and I will be delighted if you do!).

The Law of Radioactive Decay

Suppose that at the $t_0 = 0$ moment there are N_0 radioactive element atoms. Due to decay events, their number decreases exponentially with time:

$$N(t) = N_0 \cdot e^{-\lambda \cdot t}$$

where λ is the "decay constant" of a given element.



The decay constant is not very convenient in practice. For instance, if I ask you: *For such and such nucleus,* $\lambda = 2.198 \times 10^{-8}\ \mathrm{s}^{-1}$. **Would it tell you much?**

A much more convenient quantity for practical use is the so-called **"half-life"**, denoted as $\Delta t_{1/2}$. The half-life is the time period after Which the population of radioactive nuclei decreases to one-half of its initial value, i.e., to $\frac{1}{2}N_0$.

We can put it into the Decay Law:

$$\text{Since } N(t) = N_0 \cdot e^{-\lambda \cdot t}\text{, then:}$$

$$\frac{1}{2}N_0 = N_0 \cdot e^{-\lambda\cdot\Delta t_{1/2}} \Rightarrow e^{-\lambda\cdot\Delta t_{1/2}} = \frac{1}{2}$$

$$\text{If } x = y\text{, then } \ln(x) = \ln(y)\text{, so:}$$

$$\ln\left(e^{-\lambda\cdot\Delta t_{1/2}}\right) = \ln\left(\frac{1}{2}\right)$$

$$-\lambda \cdot \Delta t_{1/2} = -\ln(2)$$

$$\lambda = \frac{\ln(2)}{\Delta t_{1/2}} = \frac{0.693}{\Delta t_{1/2}} \text{ and } \Delta t_{1/2} = \frac{0.693}{\lambda}$$

So, we can write the Decay Law in terms of the half-life:

$$N(t) = N_0 \cdot e^{-0.693\frac{t}{\Delta t_{1/2}}}$$

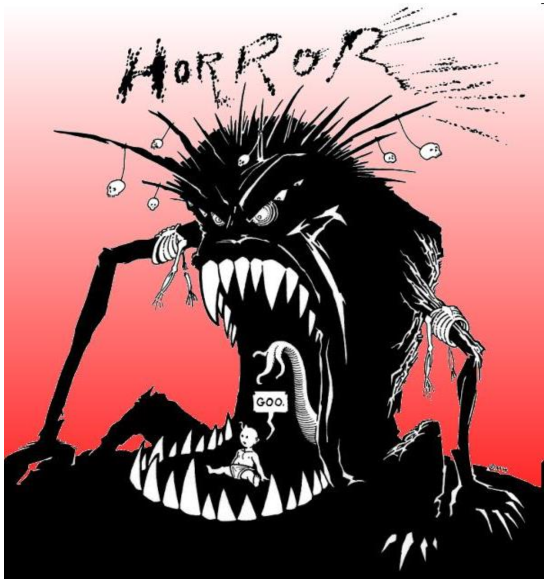
Also, we can now readily find what half-life the λ value from the preceding page corresponds to:

$$\frac{0.693}{2.198\times10^{-8}\text{ s}^{-1}} = 3.154\times10^{7}\text{ s}$$

One can readily check that this is the number of seconds in one calendar year.

Horrifying news….

1. The radiation emitted by radioac-tive substances may be highly harmful to humans



Even more horrifying:

2. Are you aware that natural Potassium is a radioactive element? And that you consume a lot of potassium in your daily food? For instance, a lot of Potassium is in bananas. Are you aware that you carry about 50 grams of a radioactive element in your body? And that in every second 6000 to 8000 radioactive decay events occur in your body?

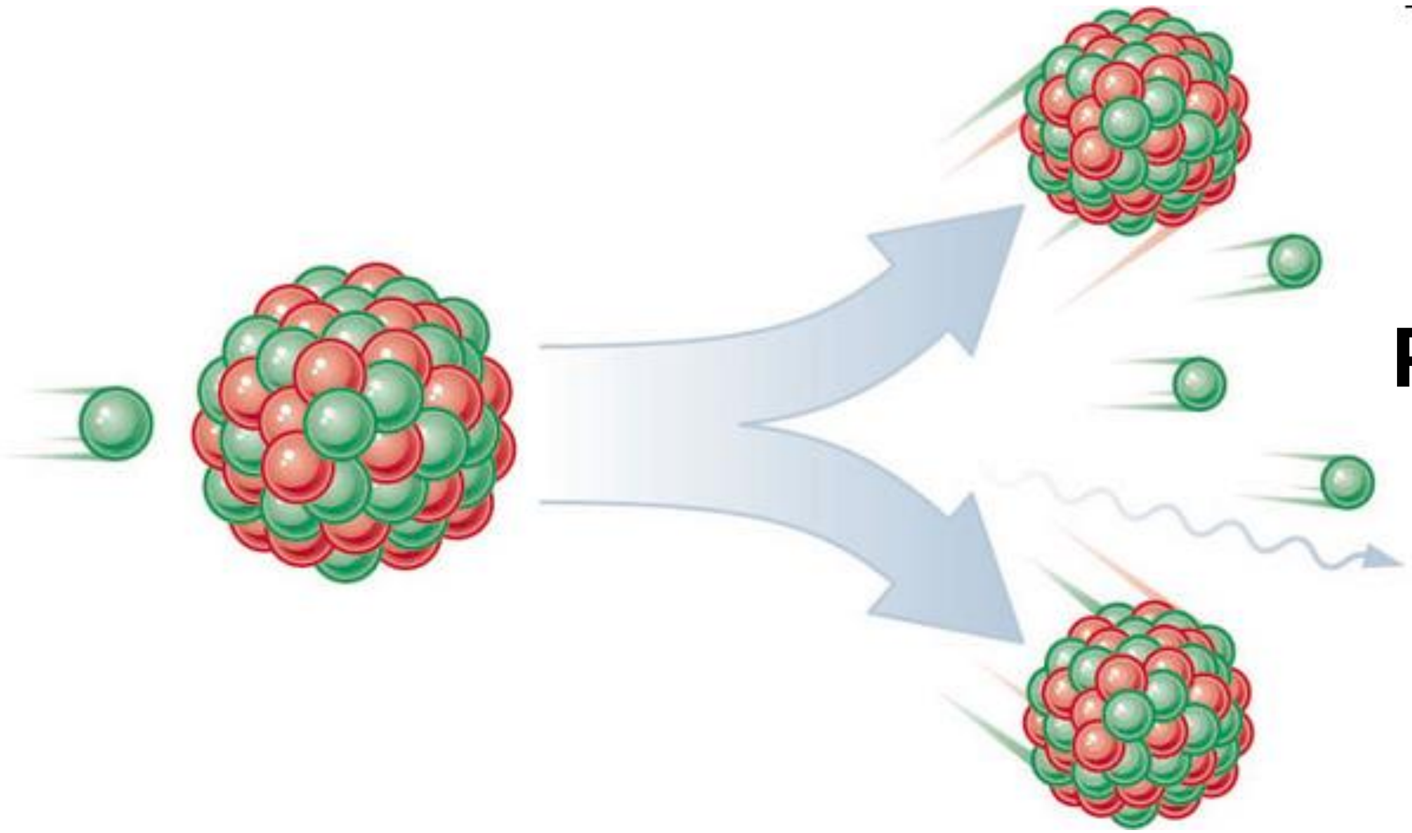
NUCLEAR FISSION

There is a small number of isotopes, with high Z values, which exhibit a peculiar behavior: namely, if the nucleus is "hit" by an impinging neutron, it absorbs it – and almost immediately the nucleus (often referred to as the "parent" one) splits into two "daughter" nuclei, usually non-symmetrically (i.e., one of the "daughters" has a markedly higher A value than the other). Much energy is released in the process, of the order of 200 MeV. The process is called a "nuclear fission", and the nuclei that undergo such process are referred to as "fissionable".

A smaller subset of such nuclei are called "fissile" – here the fission process not only produces two "daughter" nuclei, but **it releases, per average, two or more free "daughter neutrons".** It means that these daughters, in favorable circumstances, may trigger two "second generation" fission acts, which will yield four "second-generation" fission acts, and so on – there will be an avalanche increase of the rate of fission acts. The most often used term for such an "avalanche" is "chain reaction".

Nuclear Fission:

Some heavy nuclei – e.g., ^{235}U, or ^{239}Pu – if hit by a neutron, split into two “daughter” nuclei, and two or three neutrons:



Plus about 200 MeV

The two nuclei – called “fission products” – fly away with much kinetic energy, which eventually is converted to <u>thermal energy</u> Through collisions with other surrounding atoms.

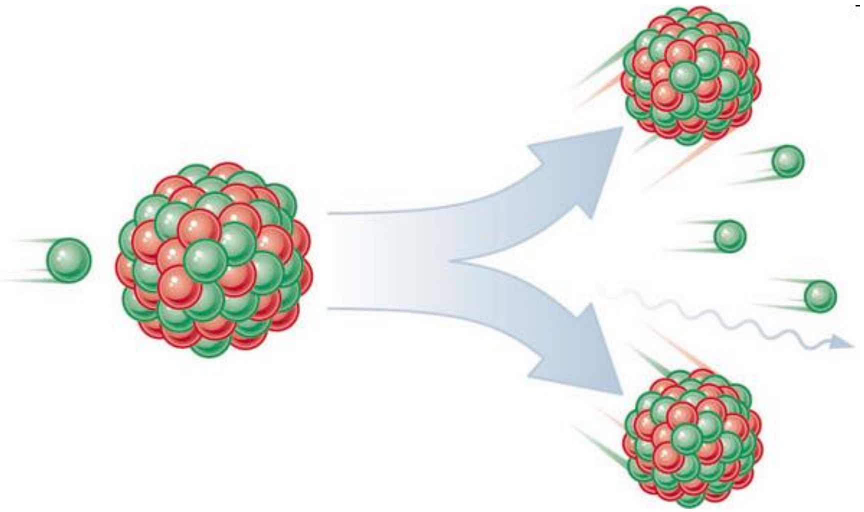
A NOTE ABOUT UNITS

Many years before the SI unit system was introduced, physicists working on micro-particles and other micro-world issues, invented an energy unit convenient to them – an electron-Volt, which is the energy gained or lost by an electron moving in electric field between two points, with the electric potential difference between them equal 1 Volt. The symbol of this unit is eV, and 1 eV = 1.6022×10^{-19} J. The energy of various processes occurring in the microworld may vary from fractions of an eV to millions of eV – so, if expressed in Joules, they will be very small numbers. Using too small or too large numbers is usually inconvenient. Therefore, physicists stubbornly keep using electron-Volts. The SI officials had to yield to this preference and the electron-Volt is a unit **tolerated** by this system.

One common misconception:

It is quite natural to think:

***The higher is the energy of the impinging neutron, the more likely it is that a fission will occur*.**



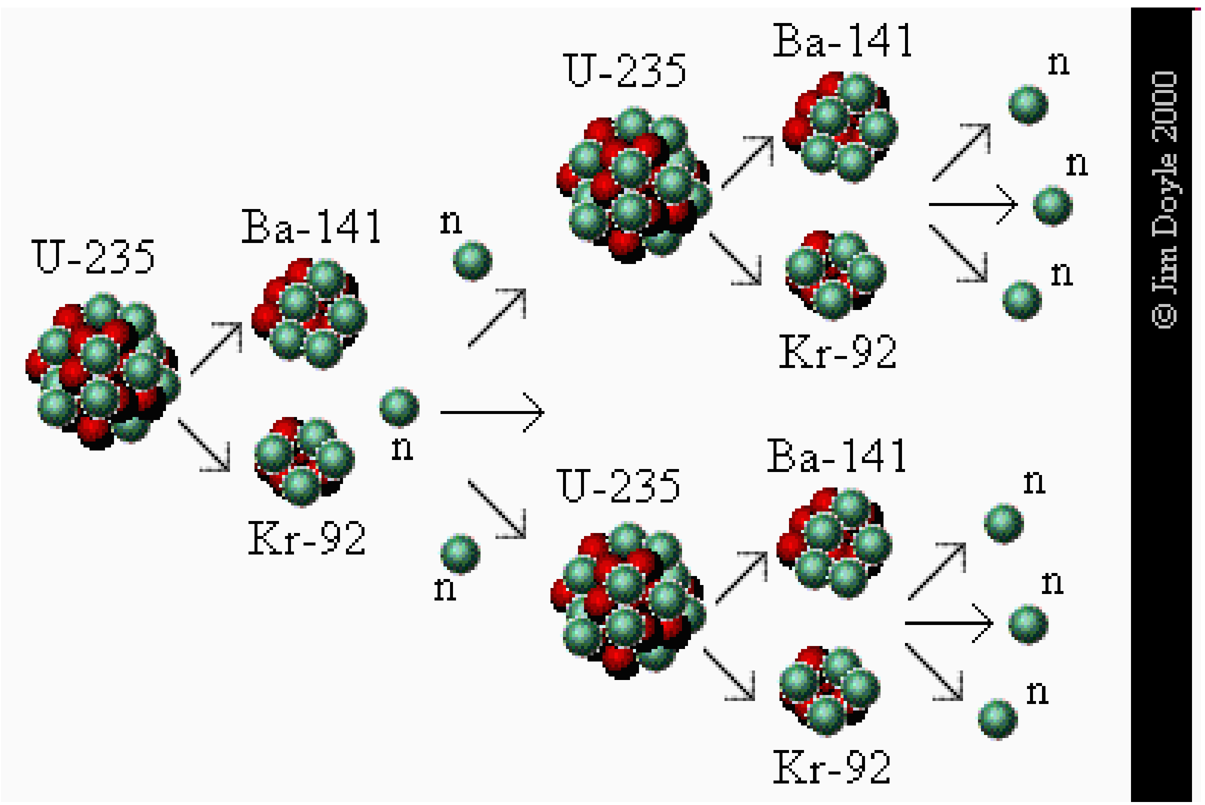
Is such thinking correct?

Answer: No! Fast neutrons seldom produce fission processes. It is the SLOW NEUTRONS that are the most effective "splitters". Why? It does not agree with common sense, does it? Surely it does not! But this is a quantum effect. To explain it in closer detail, I would need to give you first a systematic course of quantum physics… I would need at least a full quarter for that… Or even more…We don't have enough time…

So, please accept that without a proof… Would you?...

Another misconception, a "textbook-induced" one:
In many text, you will find a fission scheme similar to that shown Below: namely, the U-235 is always split into Ba-141 and Kr-92. In both text I recommended you will that information. The result? You may start thinking that this is the only possible scheme, and only Ba-141 and Kr-92 are produced in fission reaction.

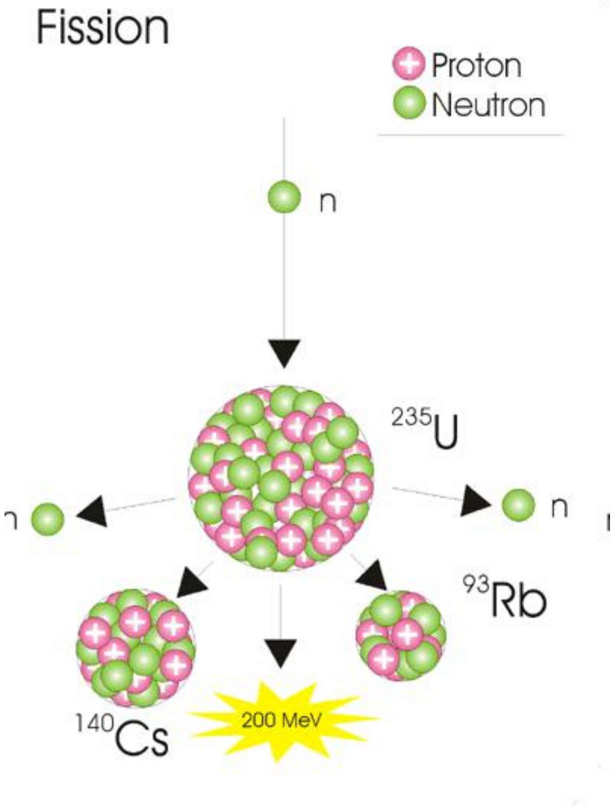
Is this true?

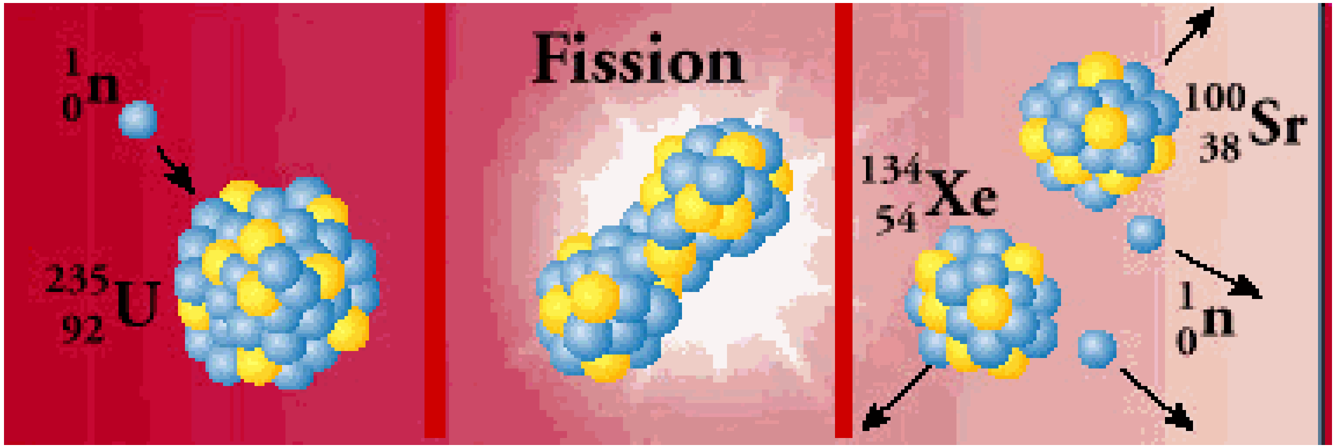


Answer: No! Not only two, but about 150 different nuclei are produced in fission events. Some other fission schemes are shown in the next slide.

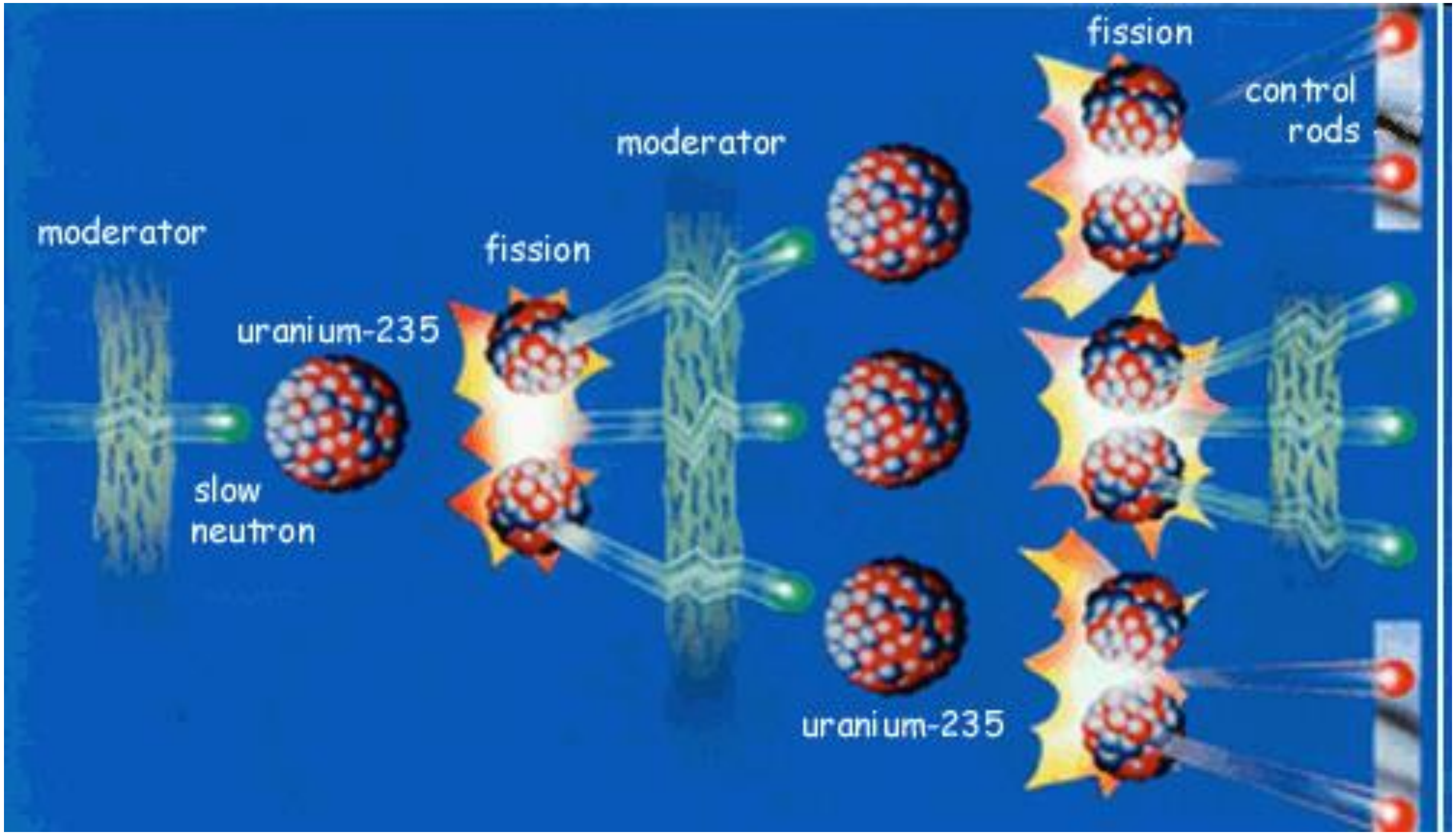
Text authors have a tendency of copying info from other texts, and therefore this misconception is "propagated" from one book to another…

Here are examples of other possible fission schemes:





Chain reaction: neutrons released in one fission event may produce up to three secondary events, and so on.



This is a good instructive graph, because it shows that neutrons have to be <u>slowed down</u> in order to split more nuclei. Fast neutrons would rather escape from the system. How are neutrons slowed down? I will tell you. Most often, using…. WATER!

MODERATION

If a chain reaction occurred in a block of pure or nearly-pure fissile material, the consequences might be catastrophic (well, sometimes this is the goal – it how nuclear weapon works). In this course, however, we want to talk only about **peaceful** applications of nuclear energy.

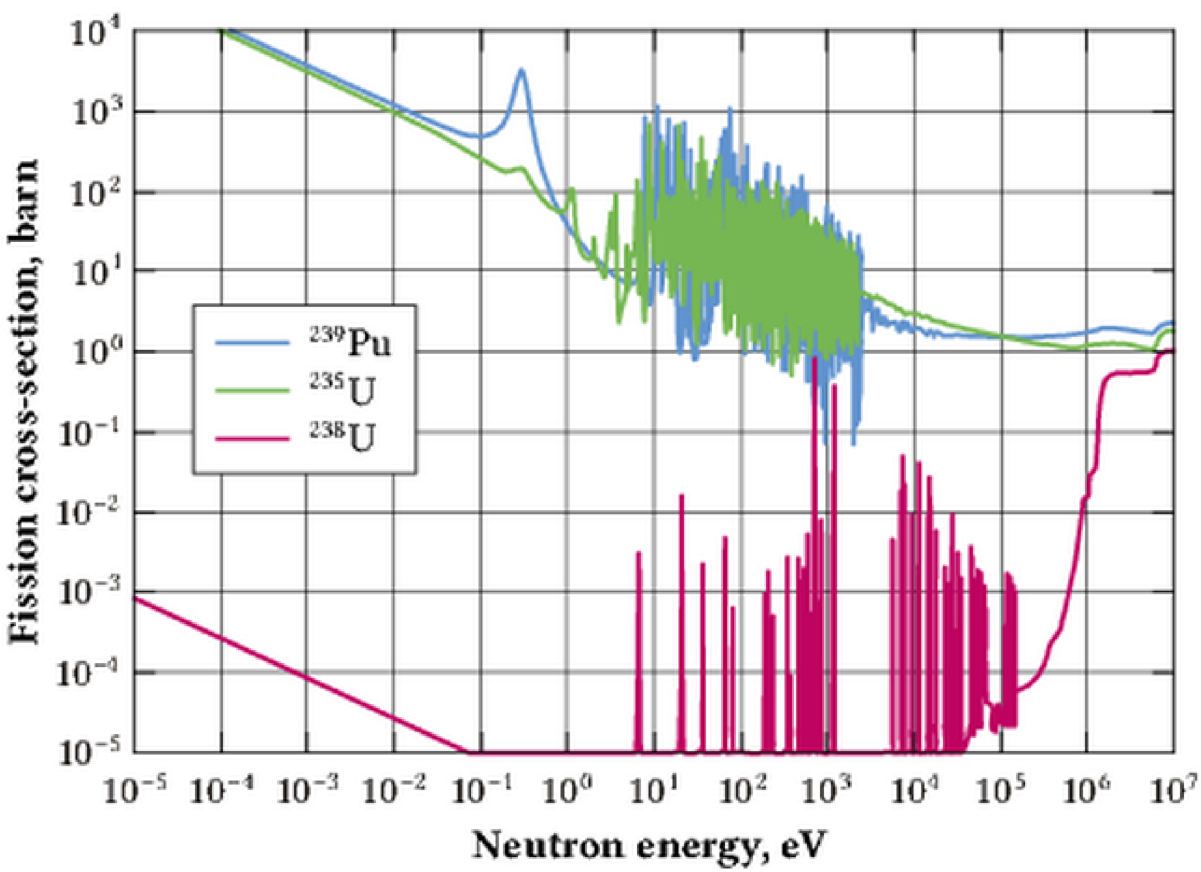
A chain reaction may release much energy that can be converted to electricity -- but only if there are means for controlling the process. There is no way of controlling the process in a bulk piece of pure fissile isotopes. The "avalanche" develops very fast, the chain reaction simply causes the material to explode. For making the chain reaction "controllable", it must be slowed down. One possible method is to increase the average distance between the fissile nuclei. It can be done by "diluting" the nuclear fuel, i.e., to mix it with a larger amount of a "neutral" material.

Mother Nature has already prepared such a “nuclear fuel” for us. It’s simply natural uranium. It’s is a mixture of two isotopes – 99.3% of Uranium-238, which is not fissile, and 0.7% of Uranium-235, which is.

But there is a problem with such “fuel” – U-238 is not “neutral”, it also fissionable – **but not fissile**.It means that it gladly absorbs fission neutrons from U-235, but gives no neutrons back. In other words, it “kidnaps” fission neutrons, so that a chain reaction cannot occur in such mixture.

There is, however, a “trick” one can use to deal with the kidnapper. Its kidnapping cannot be totally eliminated, but strongly diminished and rendered ineffective.

The thing is that the fission neutrons emerging from split U-235 nuclei are “fast neutrons”, with energies of several Mega-electronVolts. And in the graph below it is shown “how good” U-235 (green curve) and U-238 (purple? curve) nuclei are in capturing impinging neutrons. This property of a nucleus is called by physicists its “cross section”. In the graph, you can see the cross sections for U-235 and u-238 plotted as functions of neutron energy (the light-blue curve is for plutonium, please ignore it).



As you can see, in the region above 1 million electronVolts, the value for U-238 is not much lower, than that for U-235 – and since there are about

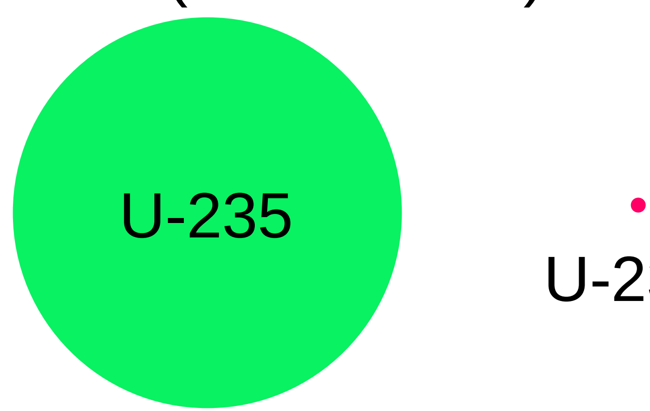
What's the "cross section"? Suppose that a particle flies towards an atomic nucleus. It "sees" is as a circular "target" of certaiUn surface area – call it "sigma" (σ). This σ is what we call the "cross section".

The behavior of nuclear cross sections for impinging particles is weird. It's ruled by the laws of the quantum world which are completely different from the laws governing the **macro world** in which we live. It's often completely **counterintuitive.**

For fission neutrons ($K > 1$ MeV):

U-235 U-238

For slow neutrons ($K < 0.1$ eV):



U-238

140 atoms of U-238 for each U-235 atom, the latter have a very little chance for “capturing” a fission neutron; an overwhelming majority of them will be “kidnapped” by U-238.

There is a remedy for the above problem, however – look at the left side of the graph. It shows that for energies of 0.1 eV and lower the cross section values for U-235 is over seven “grid units” higher than than those for U-238. The graph is in log-log scale, each grid unit corresponds to multiplication by 10 – hence, in the said region the cross section for U-235 becomes over 10 million times higher than that for U-238. So, there will be a negligibly small rate of “kidnapping”.

So, the trick is to “slow down” the fission neutrons as quickly as possible. One method, very widely used, is to make the natural uranium fuel in the form of a bundle of thin rods, and surround the rods with a “moderator” – a material in which neutrons may only **collide** with the constituent nuclei **without being absorbed**. There is a number of such materials in which the nuclei have practically “zero apetite” for swallowing neutrons. The neutrons only collide with them and are bounced out of their “flight paths". So, the neutrons move along "zig-zag" paths, and at each collision event they lose some of their kinetic energy *K*.

As was demonstrated by the experiment performed in class, a light object colliding with a much heavier one only bounces back, losing very little of its *K*. In contrast, when there is a collision with an object with similar mass, the "bouncer- object" may pass a large portion of its *K* to the "bounced" object. In view of the above, the best candidates for moderators are materials composed of light atoms.

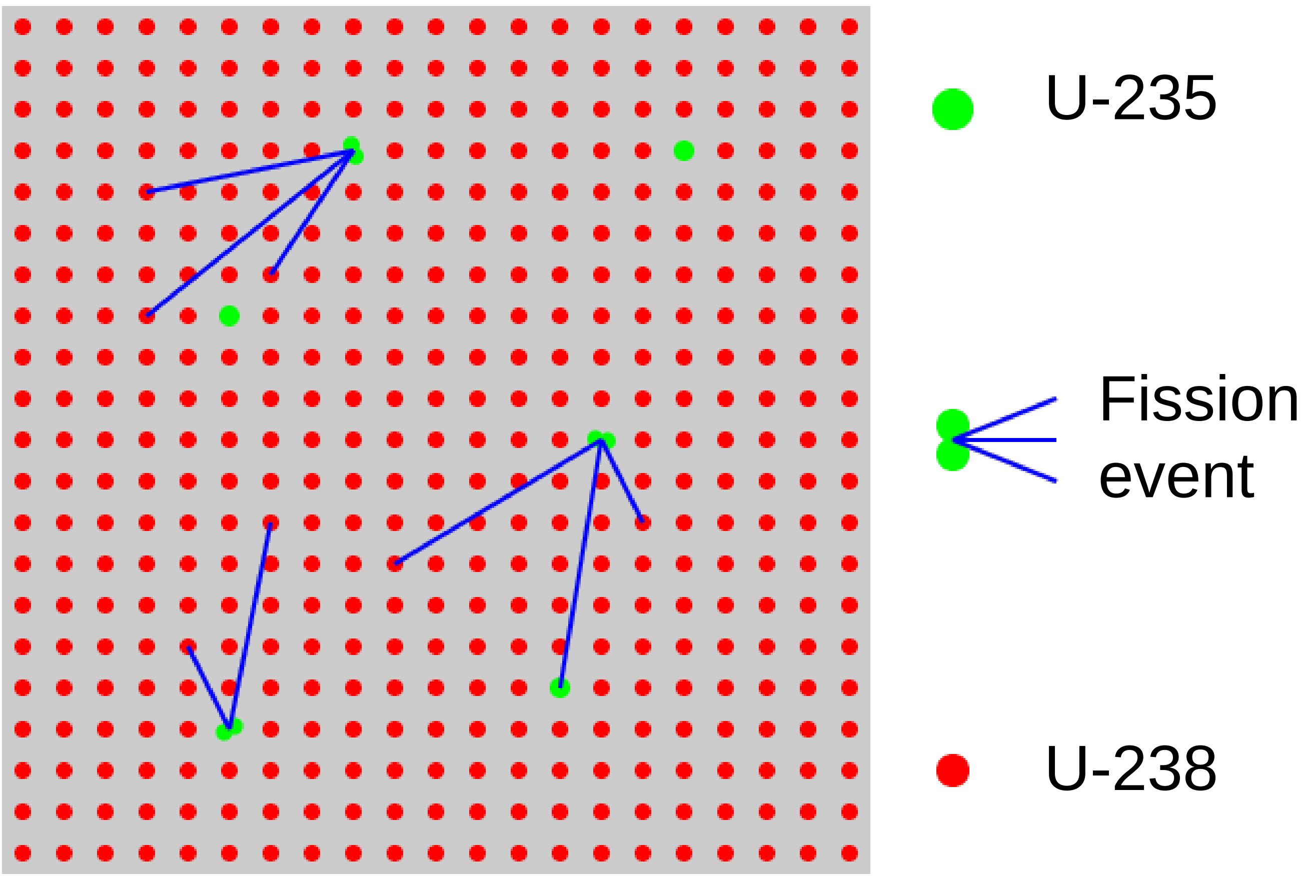
The lightest of all atoms is Hydrogen, in which the atomic nucleus is a single proton. It has indeed the highest "moderation rate" of all elements, only about 30 collisions per average are sufficient for slowing down a neutron from 1 million eV to an energy below 0.1 eV. However, protons do have an "apetite" for "pairing up" with neutrons and forming a Deuterium nucleus. Therefore, water is not a perfect moderator if one wants to use natural uranium fuel. But Deuterium nuclei do not have much apetite for incorporating yet another neutron. Therefore, "heavy water", D_2O, is an excellent moderator.

So, fast fission neutrons manage to escape from thin fuel rods before U-238 has a chance of “kidnapping” them – then, they enter ther moderator, which slows it down and if they re-enter a fuel rod after undergoing several collisions, their energy is so low that they are practically immune to the “U-238 kidnapping”, and they trigger a new fission event with the first U-235 nucleus they encounter.

What has been outlined above is nothing else than a description of how a nuclear reactor works. A well-known reactors that uses natural uranium fuel and a D_20 moderator are the Canadian CANDUs. Ordinary water, for reasons mentioned above, has a too-high absorption for working with natural uranium fuel. If the fuel is “enriched”, i.e., the concentration of U-235 is raised to 2.5-3.5% or so, such a a reactor will work – in fact, several hundred power reactors in the world uses the “enriched uranium + H_2O moderator” technology.

There is one more solution that would work with natural uranium – namely, if one uses a graphite (=pure carbon) moderator. The famous reactor (initially called “a pile”) built by Enrico Fermi and Leo Shillard, in

In natural uranium, with only 1 U-235 atom per 140 U-238 atoms, fission neutrons have a very small chance of reaching an U-235 atom. Almost all neutrons “kidnapped” by U-238.

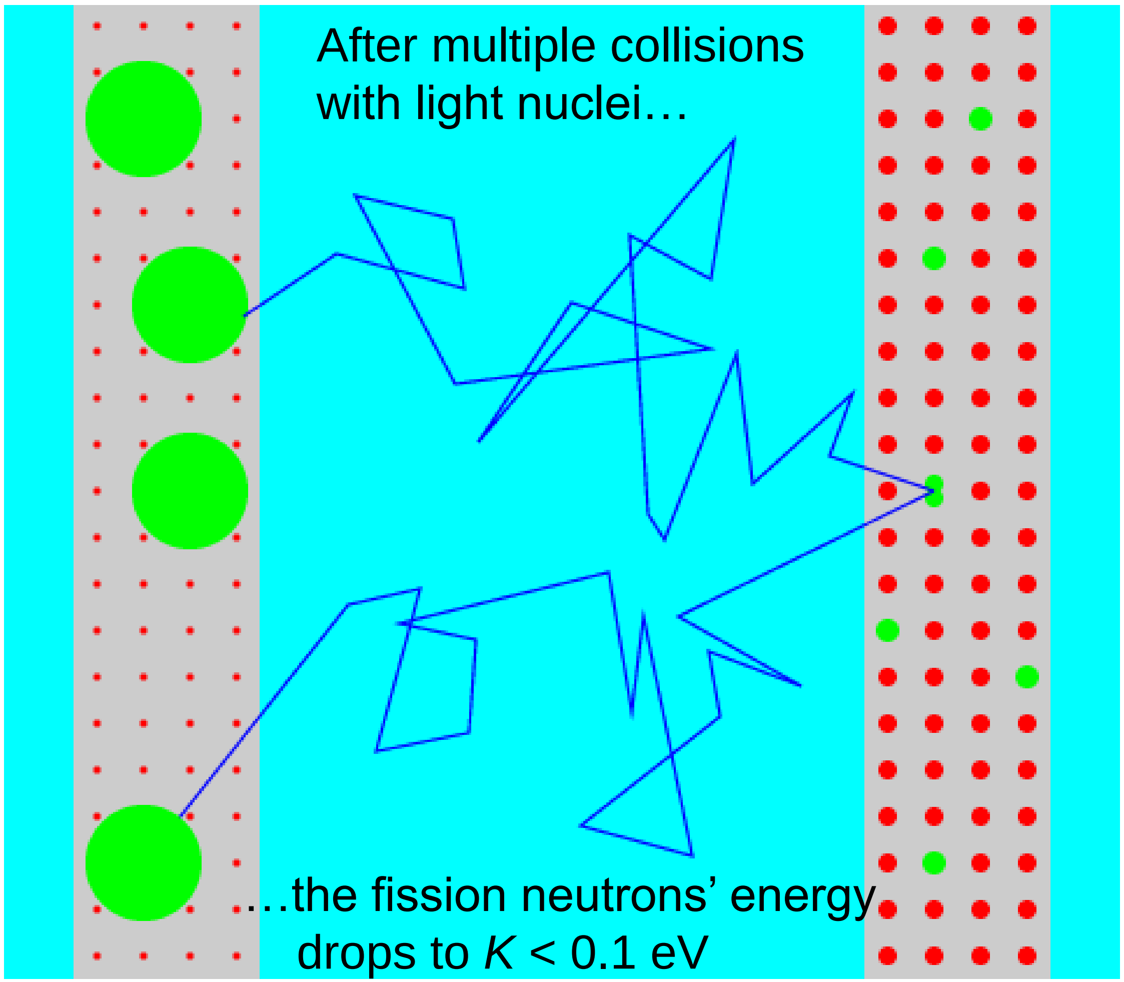


So, a chain reaction cannot occur in bulk natural uranium!
(definitely, good for us!)

NUCLEAR REACTOR:

Now if the slowed-down neutrons enter another fuel rod, they “see” a completely different situation.

Thin “fuel rods” made of natural Uranium. Now fission neutrons are able to escape to the surrounding D_2O moderator.



For slow neutrons, the U-238 nuclei become “almost invisible”, and the U-235 nuclei are strongly “inflated”, so that the neutrons may reach them now – a chain reaction may occur!

which for the first time in history a sustained and controlled chain reaction was achieved on December 2nd, 1942, used natural uranium plus a graphite moderator.

A BIT OF INTERESING HISTORY – NO NEED TO READ

By the way, when we talked about hydroelectric power, I showed a photo of the famous Norwegian hydropower plant at Rjukan – where, during the Nazi occupation of Norway (1940-45) heavy water was being extracted from normal water, using a method involving electrolysis, for which a vast amount of electric power was needed. The Nazi regime was conducting vigorous research with the objective of building nuclear weapon. The scientists working in this program correctly assumed (as Fermi did) that the first step should be building a nuclear reactor. Yet, they disqualified graphite as an appropriate moderator because their experimental tests showed that it was too strong a neutron absorber. They were not aware, though, that the absorption they observed was not an intrinsic property of graphite, but was caused by impurities which their purifying process was not able to remove.

Therefore, they switched to heavy water – and if the two sabotage actions carried out in Rjukan by the British commandos, they might have achieved a sustained chain reaction before the downfall of the Nazi state. Using all the heavy water they had managed to obtain, they built a prototype reactor, based on a concepts similar to Fermi's. This device was too small – but if increased in size by a factor of two, what would be possible, if the heavy water from Rjukan were delivered to the Third Reich – it could have reached "criticality", as the Fermi "pile" had reached 2 ½ years earlier.

Nuclear fission and types of nuclear reactor

- Like all other thermal power plants, nuclear reactors work by generating heat, which boils water to produce steam to drive the turbogenerators. In a nuclear reactor, the heat is the product of nuclear fission.
- Uranium and plutonium nuclei in the fuel are bombarded by neutrons and split usually into two smaller fragments, releasing energy in the form of heat, as well as more neutrons. Some of these released neutrons then cause further fissions, thereby setting up a chain reaction.
- The neutrons released are 'fast' neutrons, with high energy. These neutrons need to be slowed down by a moderator for the chain reaction to occur.
- In BWRs (boiling water reactors) and PWRs (pressurized water reactors), collectively known as LWRs (light water reactors), the light water (H_2O) coolant is also the moderator.
- PHWRs (pressurized heavy water reactors) use heavy water (deuterium oxide, D_2O) as moderator and coolant. Unlike LWRs, they have separate coolant and moderator circuits.
- The chain reaction is controlled by the use of control rods, which are inserted into the reactor core either to slow or stop the reaction by absorbing neutrons.
- In the Candu PHWR, fuel bundles are arranged in pressure tubes, which are individually cooled. These pressure tubes are situated within a large tank called a calandria containing the heavy water moderator. Unlike LWRs, which use low-enriched uranium, PHWRs use natural uranium fuel.
- A PWR generates steam indirectly: heat is transferred from the primary reactor coolant, which is kept liquid at high pressure, into a secondary circuit where steam is produced for the turbine.
- A BWR produces steam directly by boiling the water coolant. The steam is separated from the remaining water in steam separators positioned above the core, and passed to the turbines, then condensed and recycled.
- In GCRs (gas-cooled reactors) and AGRs (advanced gas-cooled reactors) carbon dioxide is used as the coolant and graphite as the moderator. A graphite moderator allows natural uranium (in GCRs) or very low-enriched uranium (in AGRs) fuel to be used.
- The LWGR (light water graphite reactor) has enriched fuel in pressure tubes with the light water coolant. These are surrounded by the graphite moderator. More often referred to as the RBMK.
- In FBR (fast breeder reactor) types, the fuel is a mix of oxides of plutonium and uranium; no moderator is used. The core is usually surrounded by a 'fertile blanket' of uranium-238. Neutrons escaping the core are absorbed by the blanket, producing further plutonium, which is separated out during subsequent reprocessing for use as fuel. FBRs normally use liquid metal, such as sodium, as the coolant at low pressure.
- High temperature gas-cooled reactors (HTRs), not yet in commercial operation, offer an alternative to conventional designs. They use graphite as the moderator and helium as the coolant. HTRs have ceramic-coated fuel capable of handling temperatures exceeding 1600ºC and gain their efficiency by operating at temperatures of 700-950ºC. The helium can drive a gas turbine directly or be used to make steam.
- While the size of individual reactors is increasing well over 1200 MWe, there is growing interest in small units down to about 10 MWe.

Reactor facts and performance

- Electricity was first generated by a nuclear reactor on 20 December 1951 when the EBR-I test reactor in the USA lit up four light bulbs.
- The 5 MWe Obninsk LWGR in Russia, which commenced power generation in 1954, was the first to supply the grid and was shut down on 30 April 2002.
- Calder Hall, at Sellafield, UK, was the world's first industrial-scale nuclear power station, becoming operational in 1956. The plant finally shut down on 31 March 2003.
- Grohnde, a 1360 MWe German reactor which first produced power in 1984, has generated over 347 billion kWh of electricity, more than any other reactor.
- With a cumulative load factor of 93.8% since first power in 2009, the Rajasthan 5 PHWR in India leads the way on lifetime performance, closely followed by Romania's Cernavoda 2, also PHWR.
- In August 2016, unit 2 of the Heysham II AGR plant in the UK broke the world record of 894 days continuous power production set in 1994 by Pickering 7, a Candu reactor which can be refuelled whilst on-line. As of the time of publishing, the Heysham unit had yet to be taken offline for maintenance.
- In 2015, 50 nuclear power reactors achieved load factors of more than 95%.
- Over 16,536 reactor-years of operating experience have so far been accumulated.
- Total nuclear electricity supplied worldwide in 2015 was 2441 billion kWh, about 11.5% of total electricity generated that year.

Nuclear fuel performance

- Burn-up, expressed as megawatt days per tonne of fuel (MWd/t), indicates the amount of electricity generated from a given amount of fuel.
- Typically, PWRs now operate at around 40,000 MWd/t, with an enrichment level of about 4% uranium-235.
- Advances in fuel assembly design and fuel management techniques, combined with slightly higher enrichment levels of up to 5%, now make burn-ups of up to 50,000 to 60,000 MWd/t achievable.
- With a typical burn-up of 45,000 MWd/t, one tonne of natural uranium made into fuel will produce as much electricity as 17,000 to 20,000 tonnes of black coal.

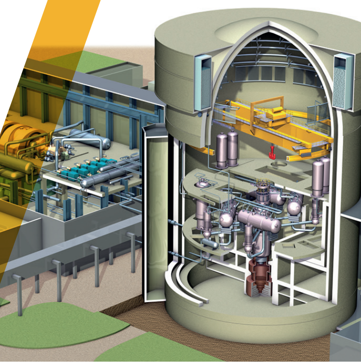
Nuclear power reactor types: typical characteristics

Characteristic	PWR	BWR	AGR	PHWR (Candu)	LWGR (RBMK)	FBR
Active core height, m	4.2	3.7	8.3	5.9	7.0	1.0
Active core diameter, m	3.4	4.7	9.3	6.0	11.8	3.7
Fuel inventory, tonnes	104	134	110	90	192	32
Vessel type	Cylinder	Cylinder	Cylinder	Tubes	Tubes	Cylinder
Fuel	UO_2	UO_2	UO_2	UO_2	UO_2	PuO_2/UO_2
Form	Enriched	Enriched	Enriched	Natural	Enriched	-
Coolant	H_2O	H_2O	CO_2	D_2O	H_2O	Sodium
Steam generation	Indirect	Direct	Indirect	Indirect	Direct	Indirect
Moderator	H_2O	H_2O	Graphite	D_2O	Graphite	None
Number operable*	282	78	14	49	15	3

*as of 31.12.15

WORLD NUCLEAR ASSOCIATION

2016/17
Pocket Guide



Nuclear Power Reactor Characteristics

www.world-nuclear.org

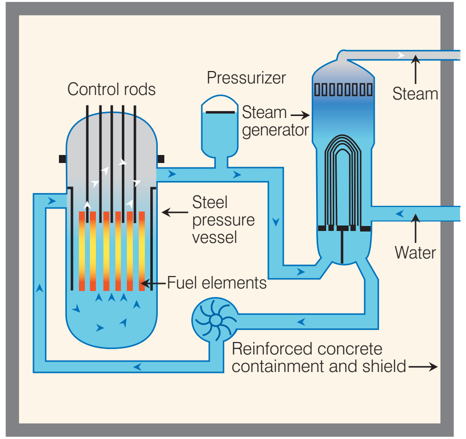
Nuclear power & reactors worldwide

Location	Nuclear electricity generation, 2015 (billion kWh)	Share of total electricity production, 2015 (%)	Number of operable reactors*	Nuclear generating capacity* (MWe)
Argentina	6.5	4.8	3	1627
Armenia	2.6	34.5	1	376
Belgium	24.8	37.5	7	5943
Brazil	13.9	2.8	2	1901
Bulgaria	14.7	31.3	2	1926
Canada	95.6	16.6	19	13,553
China	161.2	3.0	32	26,967
Czech Rep	25.3	32.5	6	3904
Finland	22.3	33.7	4	2741
France	419.0	76.3	58	63,130
Germany	86.8	14.1	8	10,728
Hungary	15.0	52.7	4	1889
India	34.6	3.5	21	5302
Iran	3.2	1.3	1	915
Japan	4.3	0.5	43	40,480
Mexico	11.2	6.8	2	1600
Netherlands	3.9	3.7	1	485
Pakistan	4.3	4.4	3	725
Romania	10.7	17.3	2	1310
Russia	182.8	18.6	35	26,053
Slovakia	14.1	55.9	4	1816
Slovenia	5.4	38.0	1	696
South Africa	11.0	4.7	2	1830
South Korea	157.2	31.7	25	23,017
Spain	54.8	20.3	7	7121
Sweden	54.5	34.3	9	8849
Switzerland	22.2	33.5	5	3333
Ukraine	82.4	56.5	15	13,107
UK	63.9	18.9	15	8883
USA	798.0	19.5	99	98,990
Total**	2441	11.5	440	384,006

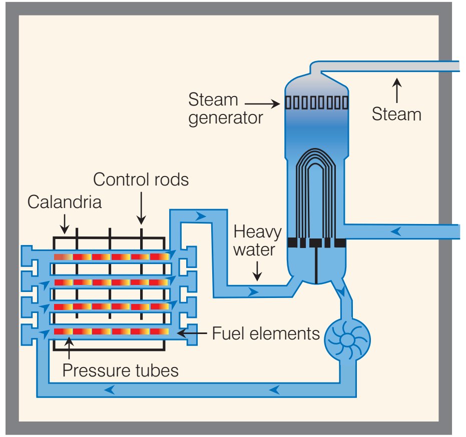
*as of 06.06.16

Sources: World Nuclear Association, IAEA

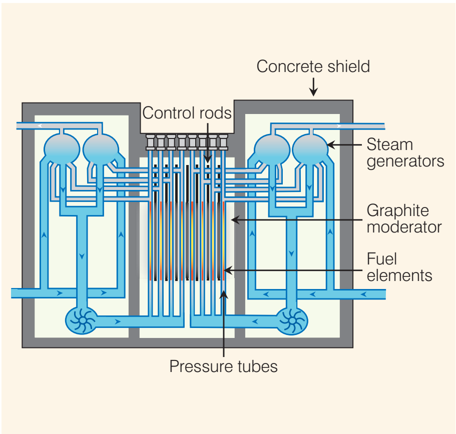
**The world total includes six reactors on Taiwan with a combined capacity of 4927 MWe, which generated a total of 35.1 billion kWh in 2015, accounting for 16.3% of its electricity generation.



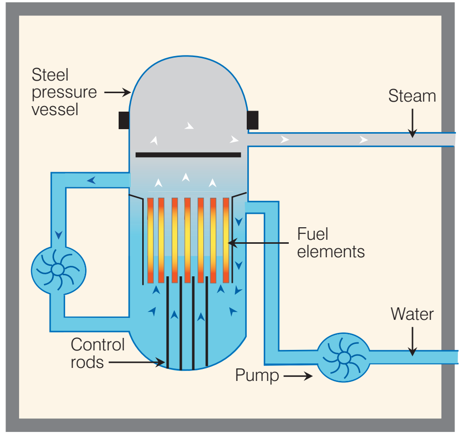
Pressurized water reactor (PWR)



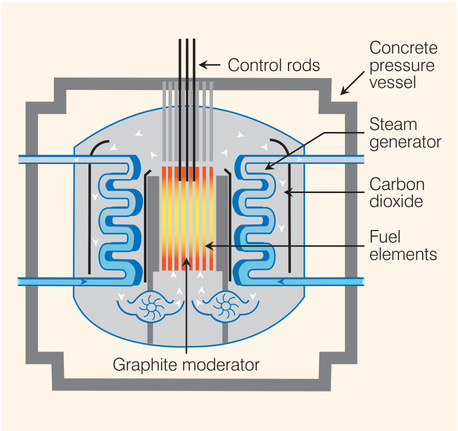
Pressurized heavy water reactor (PHWR/Candu)



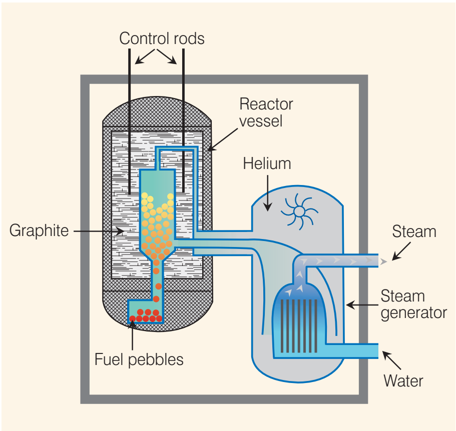
Light water graphite-moderated reactor (LWGR/RBMK)



Boiling water reactor (BWR)



Advanced gas-cooled reactor (AGR)



High-temperature reactor (HTR)

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NEXT TWO PAGES: TYPES OF NUCLEAR REACTORS, AND NUCLEAR POWER GENERATION WORLWIDE

Only if you want to learn more about fission reactors: here are links to two more good articles: one article, and another article. But it's not mandatory to read them, no questions about something that can be found only in these articles, but not in the present PDF document, will appear in the exams or quizzes.

FUSION REACTORS – there is a slight hope that they may become a reality during your lifetime – but certainly not Dr. Tom's lifetime. So, we will not talk about them in this course ☹.