

Natural Radioactivity

Overview

Nuclei consist only of protons and neutrons. The number of (positively-charged) protons in a nucleus determines how many (negatively-charged) electrons will encircle it, thus determining its position in the periodic table of elements. The number of protons in a nucleus is also called the atomic number.

Neutrons have no effect on the chemical properties of an element. They only change the mass of a nucleus, also known as the atomic weight. Nuclei with the same number of protons (same element), but different numbers of neutrons (different atomic weight) are known as isotopes. The atomic weight of an isotope is equal to the number of protons plus the number of neutrons it has.

Neutrons and protons can interact with all four of the fundamental forces. In particular, it is the strong nuclear force which holds the protons in a nucleus together, even though the protons strongly repel each other electrostatically. However, in point of fact, the strong force cannot hold even two protons together unless there is also at least one neutron present to provide extra “glue”. Because they have no charge, neutrons can increase the strong force acting in a nucleus without increasing the electrostatic repulsion. Roughly speaking, you always need about one neutron per proton to create a stable nucleus. Fewer neutrons than this, and the nucleus tends to fly apart from electrostatic repulsion.

Quantum States and the Nucleus

The quantum mechanics of the strong and weak nuclear forces inside the nucleus is similar to that of an electron interacting with the electromagnetic force, such as we studied when looking at the line spectra of neon and other gases. In both cases, (1) everything that happens can only be described in terms of probabilities, (2) if it is not absolutely forbidden, then it is mandatory, and (3) everything exists within the context of quantum states that the particles jump into and out of.

However, there are also some major differences. Probably the most bizarre is exactly what you mean by a “different” quantum state. For an electron interacting with electromagnetism, a different state means that the electron has a different energy, a different spatial pattern for where it might be found, etc. For the nuclear forces, on the other hand, a different quantum state usually means that the particle is – a different particle. It is hard to grasp the concept that the neutron is, within and of itself, a quantum “state”, and similarly, that the proton is a different quantum “state”, but when it comes to the strong and weak nuclear forces, that is exactly the case.

The radioactive decay of the neutron (discussed in more detail in the *Five Common Particles* document), is simply a case of a quantum jump intermediated by the weak nuclear force from a (slightly) higher-energy state to a lower one, exactly like an electron jumping from one energy level to another in an atom and giving off a photon. The only difference is, instead of jumping between atomic energy levels like the electron, the neutron “jumps” to being a proton, and rather than creating and emitting a photon, the neutron creates and emits an electron and an anti-neutrino.

The strong force acts only between neutrons and protons and is responsible for α -decay. The weak force acts between all known particles with a rest mass. Thus, we know that neutron decay must be intermediated by the weak force, because the strong force cannot create electrons or neutrinos. All β -decays must be intermediated by the weak nuclear force, because by definition, a β -particle is a high-energy electron.

α -Decay

An α -decay occurs when a radioactive nucleus emits an α -particle, which is a very heavy particle consisting of two neutrons and two protons. (That is, an α -particle is basically a helium atom moving at about 5% the speed of light, except without the electrons.) Classically, if I put a marble in a dish then the marble cannot escape from the dish unless it acquires enough energy to go up and over the lip of the dish. It doesn't matter if the lip of the dish is 1 mm high or a kiloparsec high. Classically, the marble can never get away.

Quantum mechanically, however, there is always some probability of a particle being anywhere in the Universe. Admittedly, in most circumstances the probability of a particle being found outside the region where it is allowed to be classically is so small that it boggles the imagination. Nonetheless, if I put a quantum mechanical marble in a dish then there is some probability that the marble, at some point, will simply materialize outside the dish. This does not violate conservation of energy, because the marble is at the same height whether inside or outside the dish. Classical particles must acquire enough energy to go over the lip before they can come to rest outside the dish, but quantum mechanical particles can simply vanish from one state – and appear in another. No energy input needed.

Now, the probability that our quantum mechanical marble will actually perform such an escape act depends critically on the height of the lip. The height doesn't matter to a classical marble, but to a quantum mechanical marble, defying the classical energy requirement for jumping over the lip is much easier (much higher probability) if the lip is 1 mm high rather than a kiloparsec high. Translated into nuclear terms, what this means is that α -particles confined inside nuclei that are relatively small and held together very tightly by the strong force, such as carbon-12 or oxygen-16, have no significant chance of escaping. The energy barrier is simply too high, and the corresponding quantum probabilities are astronomically too low. These nuclei are therefore considered to be “stable”.

But if we take a nucleus such as uranium-238, then we have a bloated bag with 92 protons and 146 neutrons that is just barely able to hold itself together. Classically the uranium atom is stable, because just barely is good enough classically. But quantum mechanically, the energy needed to escape from such an atom is so slight that the probability of an α -particle suddenly appearing outside the nucleus rises from the impossibly astronomical to the merely ludicrously improbable. And in fact, if you were to sit and watch a uranium atom with unwavering attention, there really is a 50% chance (no joke) that an α -particle really would materialize right beside it out of nothing (as if by magic) and speed away – at some point, in the next 4.47 billion years.

You might be wondering, why an α -particle? Wouldn't it be easier for individual protons to escape than an entire helium nucleus? The answer is: the strong force LOVES the combination of two neutrons and two protons. This particular combination is so favored quantum mechanically that it is almost indestructible. It is so favored that nuclear physicists don't even consider large nuclei such as uranium to consist of 92 protons and 146 neutrons. Instead, they consider uranium to be made of 23 α -particles and 54 neutrons.

Let's look at some numbers. After uranium-238 emits an α -particle, it drops to an atomic weight of 234 and loses two places in the period table to become element #90, thorium. The exact masses of these nuclei are:

Uranium-238:	238.0508 u
Thorium-234:	234.0436 u
α -particle:	4.0026 u

where u = an atomic mass unit = 1.66054×10^{-27} kg. (By international agreement, this unit is defined as exactly one-twelfth of the mass of a nucleus of carbon-12.)

You will note that the mass of uranium-238 is 238 atomic mass units – almost. Ditto for thorium and helium (α -particle). If carbon has an atomic weight of 12, and a mass of exactly 12 u (by definition), then why don't the masses for all the other isotopes come out evenly as well? The answer is the power of the strong force. When chemicals react, we know that the masses of the chemicals before and after the reaction cannot be exactly the same, because heat is either liberated or added during the reaction. And since $E = mc^2$, this means there must be a very slight mass change. The same reasoning is true for nuclear reactions, but the strong force is so powerful that the mass change shows up in the 5th or 6th decimal place rather than the 15th or 16th, as it does in chemical reactions.

So, we talk about “chemical potential energy” because the mass change is so slight in chemical reactions that it is easier to think about the chemical energy in Newtonian terms: as a massless entity that somehow flows from here to there.

By contrast, no physicist talks about “nuclear potential energy”. Since the energy differences created by the strong force are so huge that you can actually weigh them, all that physicists talk about at the nuclear level is mass differences.

So, before the decay we have uranium-238 with a mass of 238.0508 u. After the decay we have thorium-234 and an α -particle with masses of $234.0436 \text{ u} + 4.0026 \text{ u} = 238.0462 \text{ u}$. Comparing before and after, we can see that $0.0046 \text{ u} = 7.64 \times 10^{-30} \text{ kg}$ of mass has vanished. Well, not really. It has been converted into energy. Almost all of this energy appears as kinetic energy for the α -particle, and doing a little math:

$$E = \frac{1}{2} mv^2 \text{ gives us: } (7.64 \times 10^{-30} \text{ kg})(3 \times 10^8 \text{ m/s})^2 = \frac{1}{2} (1.66054 \times 10^{-27} \text{ kg})(4.0026)^2 v^2$$

$$\text{or } v = 1.44 \times 10^7 \text{ m/s} = 32,190,000 \text{ miles per hour} = 4.8\% \text{ the speed of light.}$$

β -Decay

As noted in the *Five Common Particles* document on this web site, free neutrons are unstable and decay into a proton, an electron, and an anti-neutrino with a half-life of about 10.6 minutes. This reaction can only be intermediated by the weak nuclear force, because the strong nuclear force has no effect on electrons and neutrinos. However, when bound to a proton by the strong force, the strong force “forbids” the weak interaction, and hence the neutron is stable inside the nucleus.

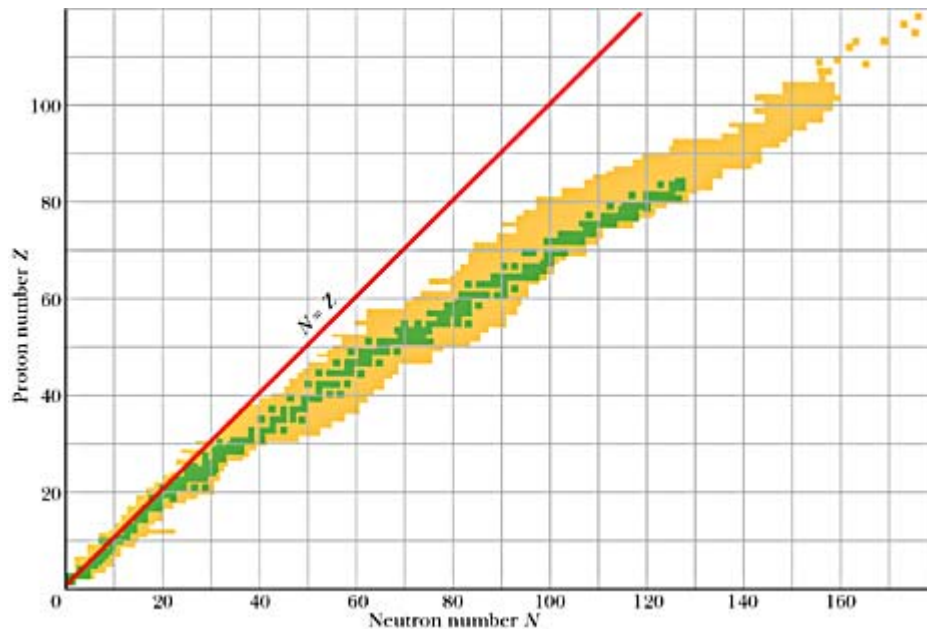
To a point. If a nucleus becomes too neutron-heavy, then there aren't enough protons to stabilize all the neutrons, and the probability that the weak interaction will cause a β -decay begins to rise. One of the most common β -emitters is carbon-14. Carbon is element number 6, and by far the most common isotope of carbon is carbon-12, where there is exactly one proton for each neutron. This isotope is extremely stable. Carbon-14, on the other hand, has two extra neutrons as compared to carbon-12, and that is two too many. This isotope is unstable, and β -decays with a half-life of 5730 years.

In β -decay, the atomic weight of the isotope does not change, but converting a neutron into a proton means that the nucleus advances one place in the periodic table. In this case, carbon-14 turns into nitrogen-14. (Note that nitrogen-14 has 7 protons and 7 neutrons, and therefore is extremely stable. Which is partly why carbon-14 isn't.)

As I've noted elsewhere, the electrons emitted in β -emission must share their energy with anti-neutrinos, and thus β -emitters give off a spectrum of energies rather than the single energy characteristic of α -emitters.

Nuclear Stability

Together, α -decay and β -decay constrain the number of possible nuclei. The chart below shows all of the known stable nuclei (green) and relatively long-lived radioactive nuclei (yellow) as a function of their proton and neutron numbers. As a rule, isotopes on the top side of the area are α -emitters (too many protons), and those on the bottom are β -emitters (too many neutrons). As can be seen, the line where $N = Z$ (number of neutrons equals number of protons) is the stability line for the lighter isotopes. The heavier isotopes need more and more neutrons as the nuclei becomes larger and have more protons repelling each other, so the stability region drifts to the right of the $N = Z$ line as you move up in the periodic table.



γ -Decay

This is easily the least interesting of the three natural forms of radioactivity, even though it is also the most dangerous. γ -decay comes from the fact that it is possible for protons and neutrons to move between different excited states in the nucleus exactly like electrons move between excited states in the other parts of the atom. When they do, they emit photons. There are two differences, however: the strong nuclear force is much more powerful than the electromagnetic force, so instead of emitting photons of visible light it emits extremely energetic photons in the γ -ray part of the spectrum. And, for complicated reasons having to do with the details of the strong force, the half-lives of excited states in the nucleus are typically on the order of years, rather than the nanoseconds that are more typical of electron transitions.