

The Five Common Particles

The world around you consists of only three particles: protons, neutrons, and electrons. Protons and neutrons form the nuclei of atoms, and electrons glue everything together and create chemicals and materials. Along with the photon and the neutrino, these particles are essentially the only ones that exist in our solar system, because all the other subatomic particles have half-lives of typically 10^{-9} second or less, and vanish almost the instant they are created by nuclear reactions in the Sun, etc.

Particles interact via the four fundamental forces of nature. Some basic properties of these forces are summarized below. (Other aspects of the fundamental forces are also discussed in the *Summary of Particle Physics* document on this web site.)

<u>Force</u>	<u>Range</u>	<u>Common Particles It Affects</u>	<u>Conserved Quantity</u>
gravity	infinite	neutron, proton, electron, neutrino, photon	mass-energy
electromagnetic	infinite	proton, electron, photon	charge
strong nuclear force	$\approx 10^{-14}$ m	neutron, proton	baryon number
weak nuclear force	$\approx 10^{-15}$ m	neutron, proton, electron, neutrino	lepton number

Every particle in nature has specific values of all four of the conserved quantities associated with each force. The values for the five common particles are:

<u>Particle</u>	<u>Rest Mass¹</u>	<u>Charge²</u>	<u>Baryon #</u>	<u>Lepton #</u>
proton	938.3 MeV/c ²	+1 e	+1	0
neutron	939.6 MeV/c ²	0	+1	0
electron	0.511 MeV/c ²	-1 e	0	+1
neutrino	≈ 1 eV/c ²	0	0	+1
photon	0 eV/c ²	0	0	0

1) MeV = mega-electron-volt = 10^6 eV. It is customary in particle physics to measure the mass of a particle in terms of how much energy it would represent if it were converted via $E = mc^2$. So, the units for mass become E / c^2 , or in this case, MeV/c².

2) e = the charge on the electron, or 1.602×10^{-19} coulomb

Every particle in nature also has an anti-particle associated with it. An anti-proton is exactly like a proton, except that all of its quantum numbers (besides the rest mass) have the opposite sign. So, an anti-proton has a charge of -1 and a baryon number of -1. Likewise, an anti-electron (also known as the positron) has a charge of +1 and a lepton number of -1.

If a particle and its anti-particle meet, they instantly neutralize each other's quantum numbers and their combined rest masses change into pure energy, i.e., a shower of photons. Inherently, a positron is as perfectly stable as an ordinary electron, in sharp contrast to most exotic particles with their extremely short half-lives. (A positron is *exactly* like an electron, except for the sign change of its quantum numbers.) But, no anti-particle can survive long despite its inherent stability, because if/when it is created at Fermilab or by a cosmic ray, it only lasts until it bumps into a normal particle, and then they both disappear in a violent flash of gamma-rays. In a world filled with ordinary matter, the only anti-matter that survives more than a fraction of a second is the tiny portion created in ultra-ultra-high vacuum chambers by physicists and held in place by magnetic fields, so that it can be studied.

Tech Note -- The simplest theories of particle physics predict that the Big Bang should have produced exactly equal amounts of matter and anti-matter, and thus the Universe should be empty except for photons. The fact that the Universe ended up with a slight excess of one type of matter over the other means that very subtle asymmetries have to be present in the fundamental forces. These asymmetries were first verified in 1956, when C. N. Yang and T. D. Lee showed that the weak nuclear force has a slight preference for creating particles that spin in one direction rather than the other. (i.e., the weak force does not produce particles spinning clockwise or counter-clockwise with 50/50 equality, as the other forces do.)

Of the five common particles, the neutrino is undoubtedly the oddest. The neutrino has a rest mass, but it is so incredibly small (probably two million times less massive than the electron!) that even a nine-volt battery has enough energy to accelerate it to 99.7% of the speed of light. The nuclear reactions that create neutrinos often impart keV or even MeV energies to them, so for all practical purposes, neutrinos move at the speed of light. There was an interesting illustration of this in 1987, when a supernova exploded 180,000 light-years from Earth. The time lag between when telescopes saw the blast, and when neutrino detectors were set off by the torrent of neutrinos created in the blast, was at most 30 minutes. A lag of 30 min over a span of 180,000 years gives a neutrino velocity of 0.9999999997 c.

The neutrino does not react with either the strong nuclear force or the electromagnetic force. That leaves only gravity and the weak nuclear force for interactions with other particles, which almost means that it doesn't interact with other particles. Gravity is effectively nonexistent at the subatomic level, and neutrinos are too "hot", i.e., too energetic and moving too fast, to be much affected on a planetary scale. Neutrinos are slightly deflected as they go by planets, like a light beam -- they never orbit anything.

The weak nuclear force does operate on the subatomic level, but there is a reason we call it the weak force. The interaction probabilities for the weak force are extremely small in the best of circumstances. When you apply them to an extremely light particle streaking past at about the speed of light (so it only takes 10^{-23} sec for it to pass an atomic nucleus), the interaction probabilities fall to stunning levels of inertness. Every moment of your life, about 10^{12} solar neutrinos pass through you *per second*, and yet you can easily go weeks without a single one being stopped by your body! Very unlike other astronomers who study the Sun, neutrino astronomers run their detectors 24 hours a day, because it doesn't make the slightest difference to them whether the Sun is in the sky or not. Solar neutrinos can pass clear through the entire bulk of the Earth as though it wasn't there, so it is never "dark" at a neutrino detector.

Which brings up an interesting question. How exactly does one detect neutrinos if they don't react with anything? Well, in the early days, we didn't detect them. We deduced them. The existence of neutrinos was first suspected in the 1920's, when physicists noticed that the electrons emitted in radioactive β -decay did NOT have constant energies -- unlike the helium nuclei in α -decay, which do show constant energies. The immediate suspicion was that the electron must be sharing its energy with a second, unseen particle, but experiment after experiment to detect a second particle failed. (And now you know why, since you have learned just how elusive the neutrino is.) The situation became so frustrating, some physicists (including Neils Bohr) seriously considered the notion that perhaps β -decay did not obey the law of conservation of energy! Finally, in 1931, Austrian physicist Wolfgang Pauli postulated the existence of the neutrino on theoretical grounds. They were not detected experimentally until 1956.

Let's look at a common particle decay to see how the neutrino comes into β -decay. Unlike the other common particles (proton, photon, electron, neutrino), the neutron is not stable on its own. It is only stable when combined with protons in an atomic nucleus. A free neutron has a half-life of only about 10.6 min, and decays like so:

neutron	→	proton	+	electron	+	anti-neutrino
Q= 0		Q= +1		Q= -1		Q= 0
B= +1		B= +1		B= 0		B= 0
L= 0		L= 0		L= +1		L= -1

Below each particle I have listed its charge, baryon number, and lepton number. All of these must be conserved in any reaction, along with mass-energy. A quick glance at the top of this paper reveals that the neutron just barely has enough mass to create a proton. But the neutron has charge $Q = 0$, whereas the proton has charge $Q = +1$, so to conserve charge another particle with $Q = -1$ must be created. If there was enough energy available, creating something like an anti-proton might be a possibility, but the mass difference between the neutron and the proton is so slight that the only particle with $Q = -1$ that can possibly be produced is the electron.

That takes care of mass-energy and charge. For baryon number, the neutron and the proton each have $B = +1$, and the electron has $B = 0$, so that balances fine. Check.

But -- the neutron has a lepton number of zero, and so does the proton, but the electron has a lepton number of +1. Ouch. Lepton number can only be conserved if we also create something which has a lepton number of -1. And at this point, in order to continue satisfying all the other conservation laws, it must also have a very small rest mass, no charge, and a baryon number of zero. If we look at the top of this paper and remember the rules, then we see that the only particle which satisfies these conditions is the anti-neutrino. And this is why β -decay always produces a neutrino (technically, an anti-neutrino) in addition to a high-energy electron (or β -particle).

And oh, yes. How does one actually detect neutrinos? Well, at the Japanese neutrino detector known as Super-Kamiokande, they have constructed a chamber 120 feet across and 130 feet high and filled it with 50,000 tons of very pure water. The walls of this behemoth are completely lined with nearly 12,000 of the largest photodetectors ever manufactured -- each one has a lens over 20 inches across. If an incoming neutrino is energetic enough (it needs to be carrying about 5 MeV), and in the extremely unlikely event that it should interact with an electron in the water, then the probability is that the electron will receive a very sharp "kick", and go rocketing off. This produces a characteristic flash of light. And all those thousands of huge-eyed phototubes are watching for exactly this.

The numbers are preposterous. The tank has approximately 10^{33} electrons in it, and something like 10^{21} solar neutrinos pour through it every day. And how many flashes do those thousands upon thousands of photodetectors lining a chamber as tall as a ten-story building, and with a floor area of 14,000 square feet, see on a good day?

Maybe 150.

You detect neutrinos by putting vast numbers of targets in the way of vast numbers of neutrinos, so that the sheer statistics will give you a "hit" maybe every 10 minutes or so, even if the typical reaction probability for a neutrino event is only one in 10^{19} .